A Day in the Life of a Mars Rover Driver

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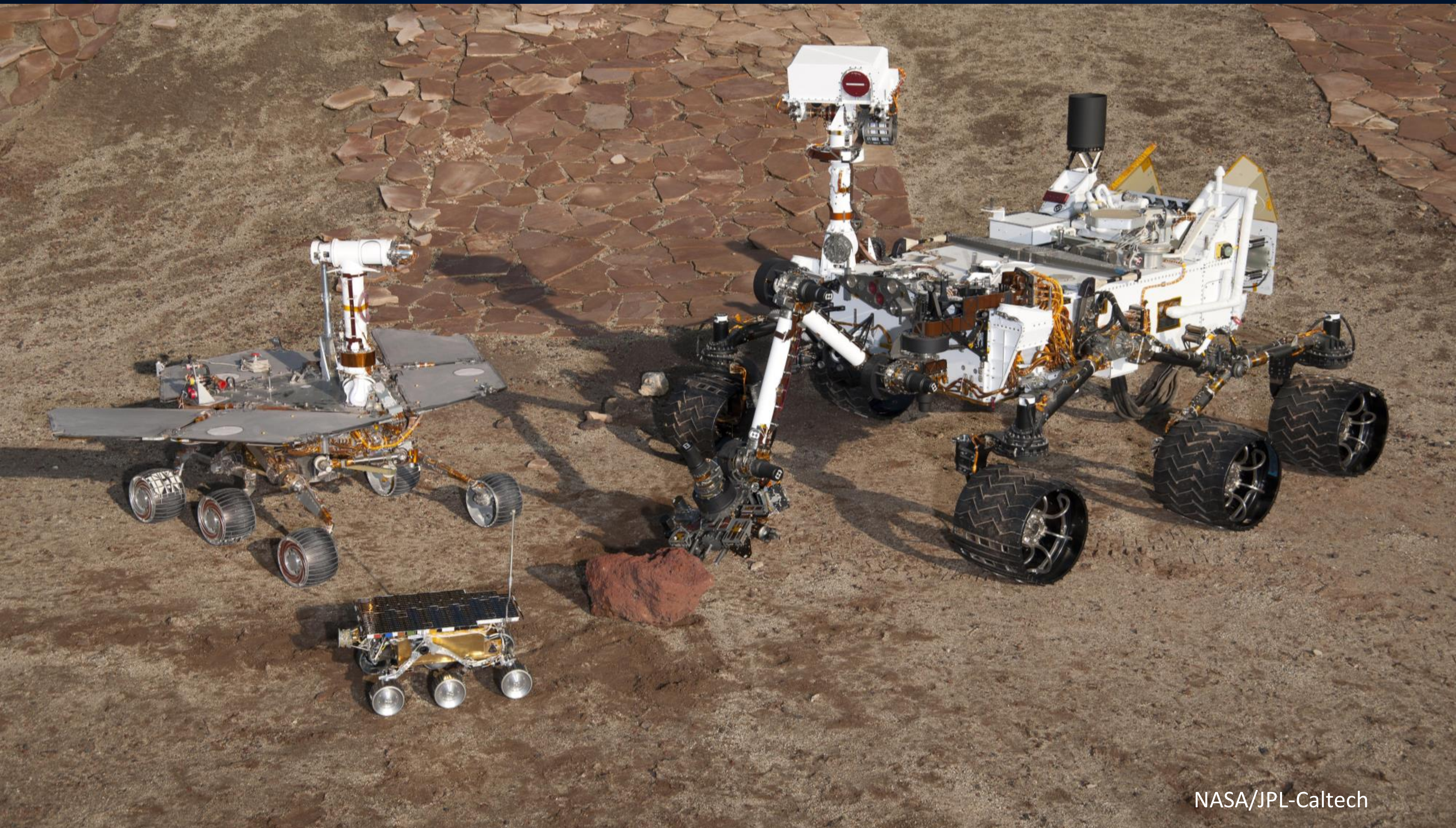
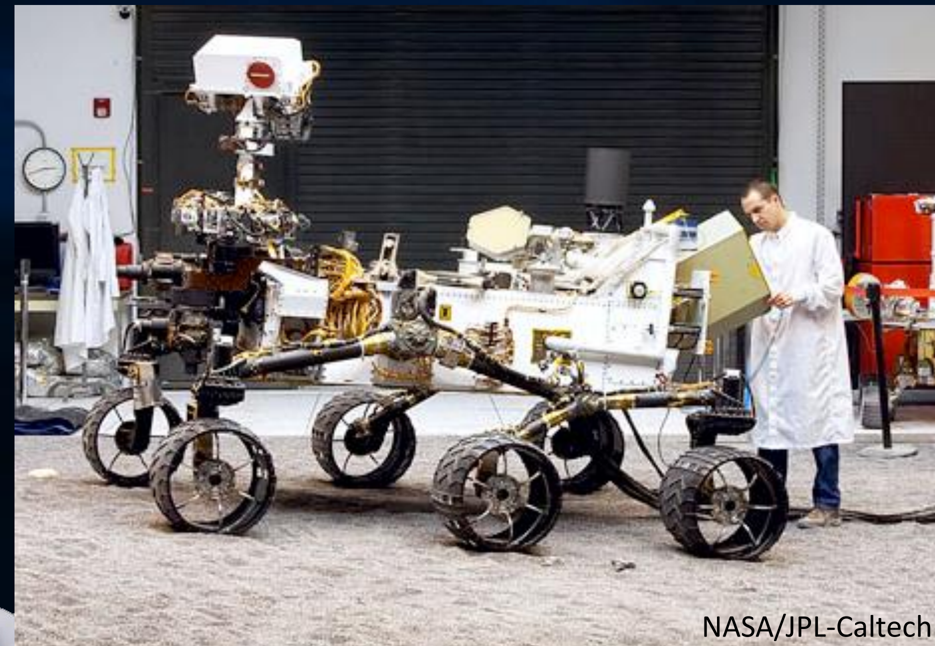
California Institute of Technology

Artist's Concept. NASA/JPL-Caltech

Mars Rover Family Portrait



[redacted]



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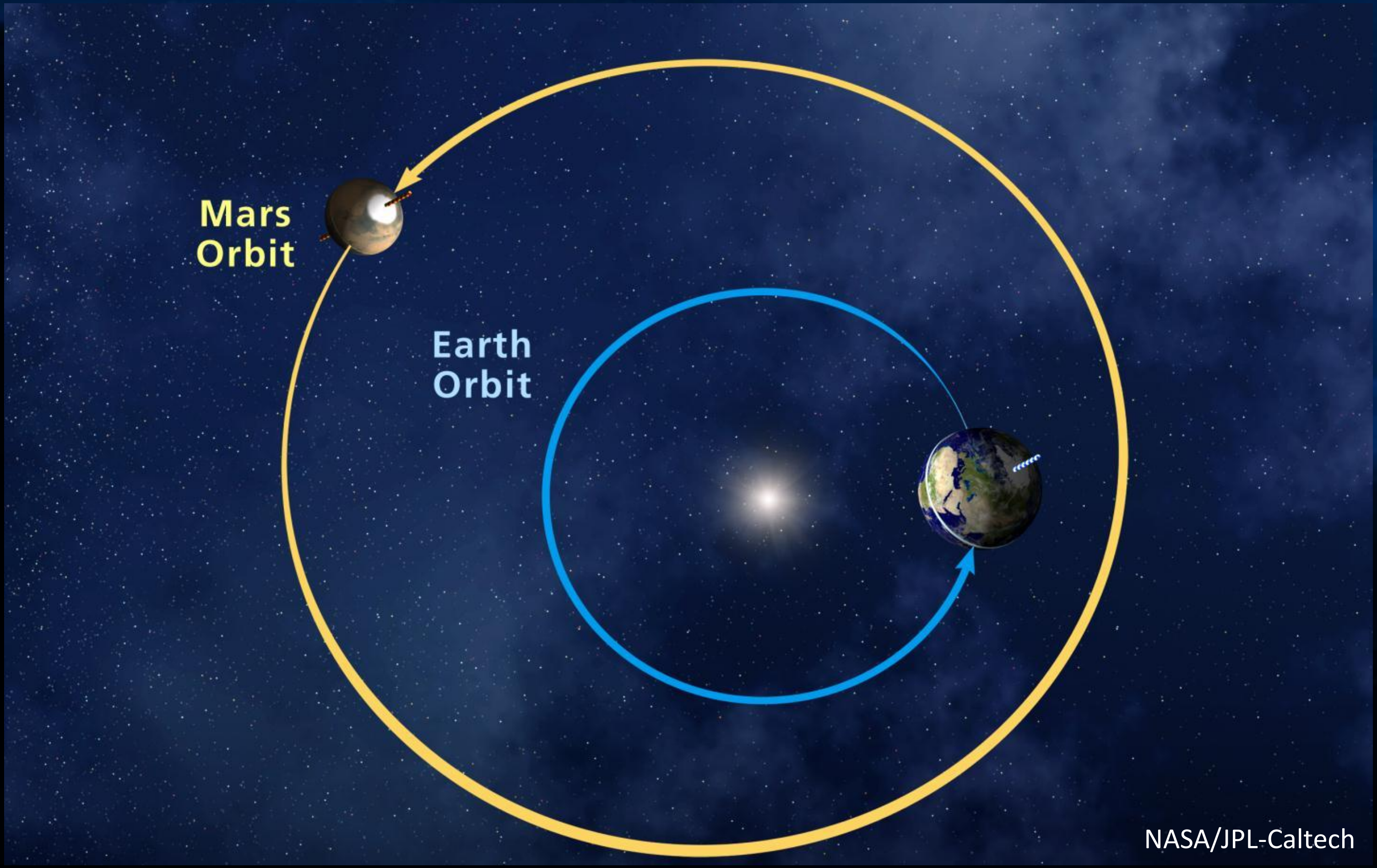
Mission Planning Cycle

Because of the distance between Earth and Mars, we can’t drive a rover in real time.



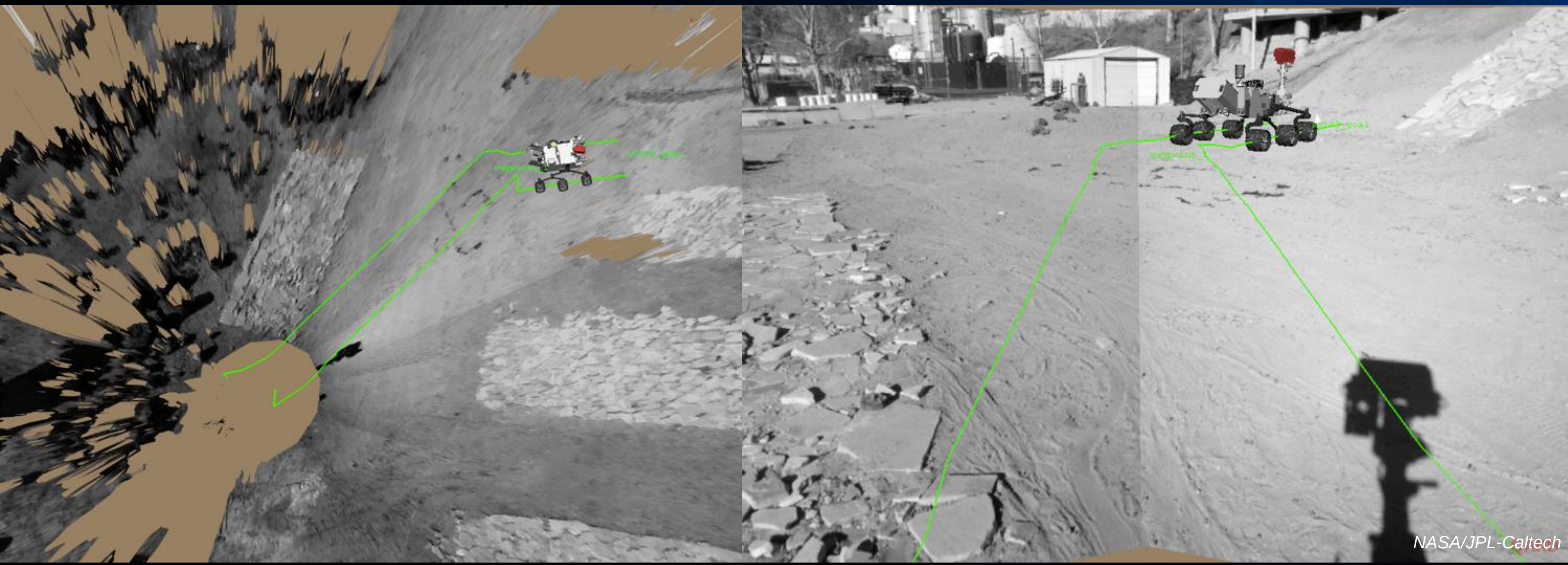
It takes between 4 and 22 minutes each way for a signal to travel between the two planets.

Also, Logistics

The Deep Space Network is a shared resource for dozens of missions.

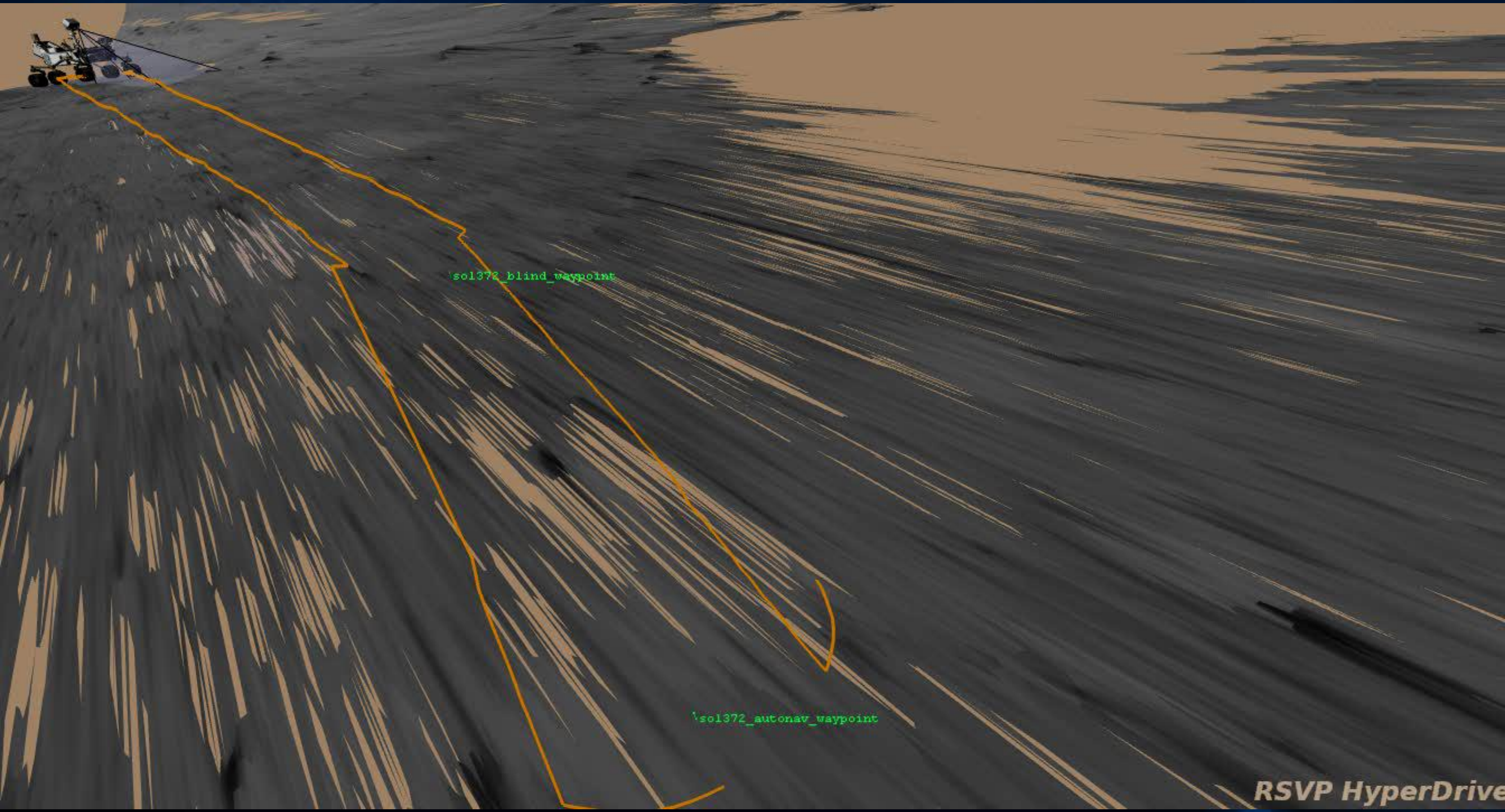
We often only get one uplink and few downlink windows each day

A previous day's images are fed into the Rover Simulation Visualization Program (RSVP) and 3D meshes are created.



Rover drivers wear shuttered 3D goggles to view stereo imagery and 3D meshes

Drives are planned in 3D meshes out to the limit of visibility



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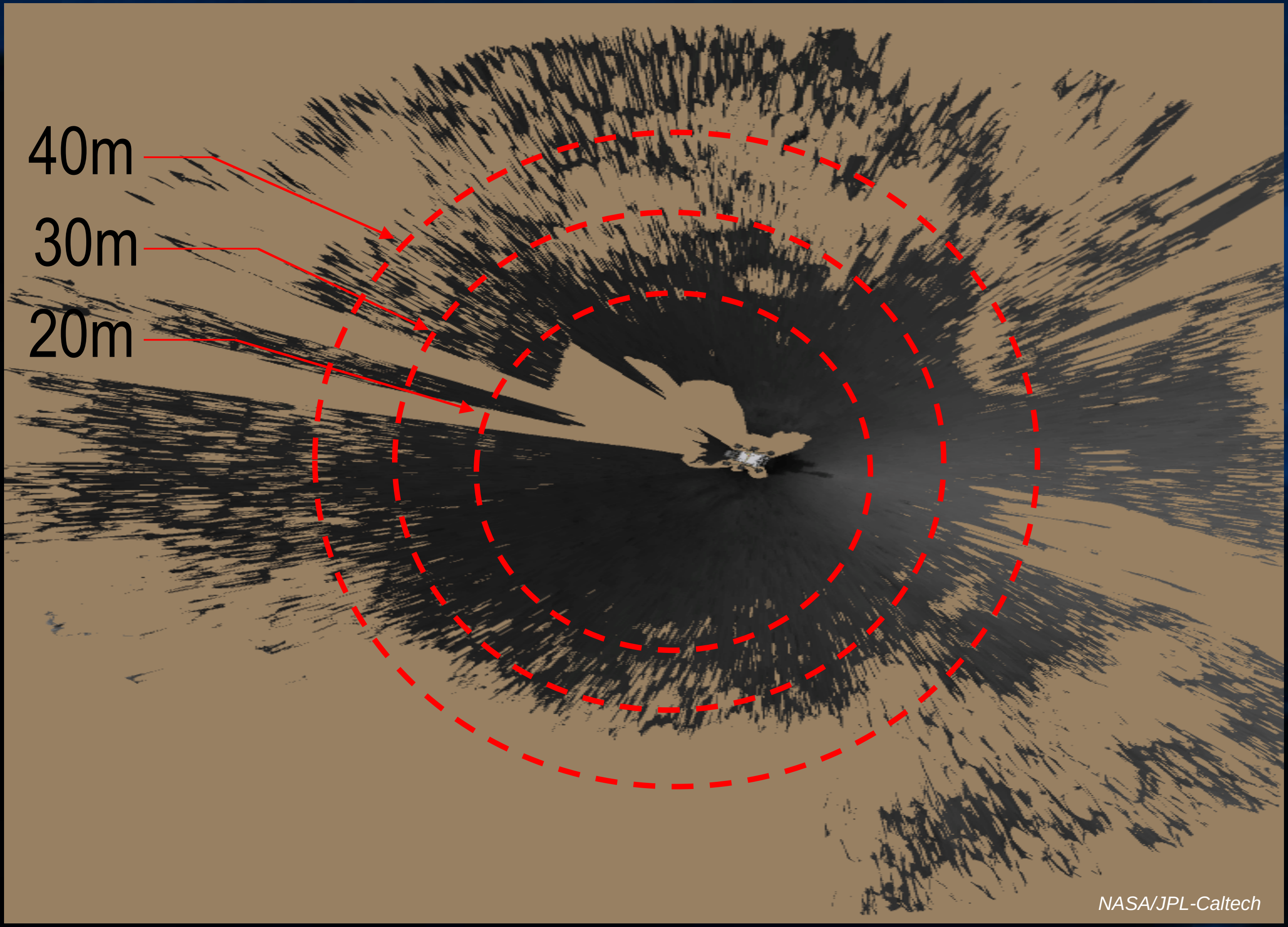
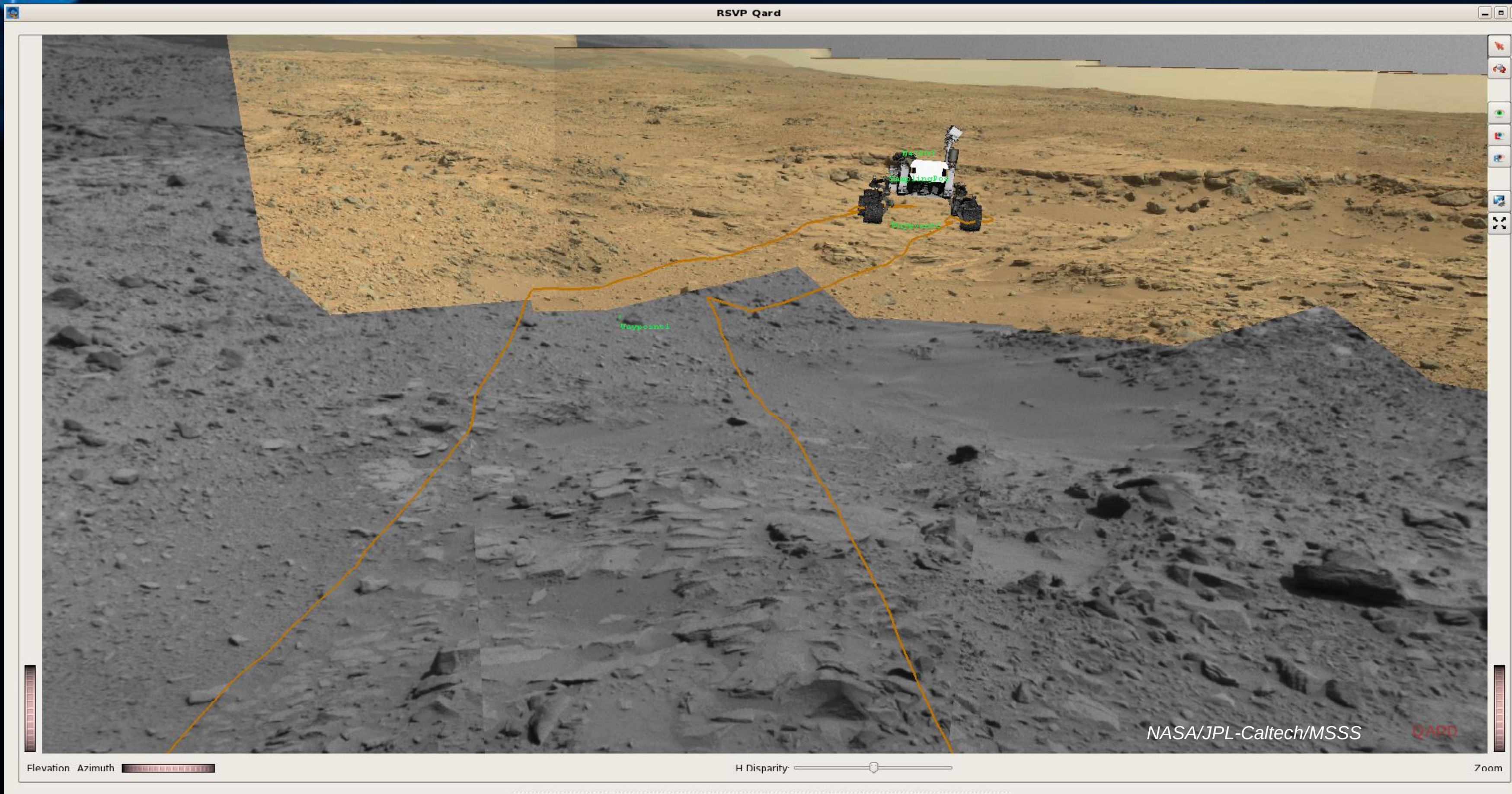
[redacted]

This image shows how much detail the Navcam cameras can typically see nearby.



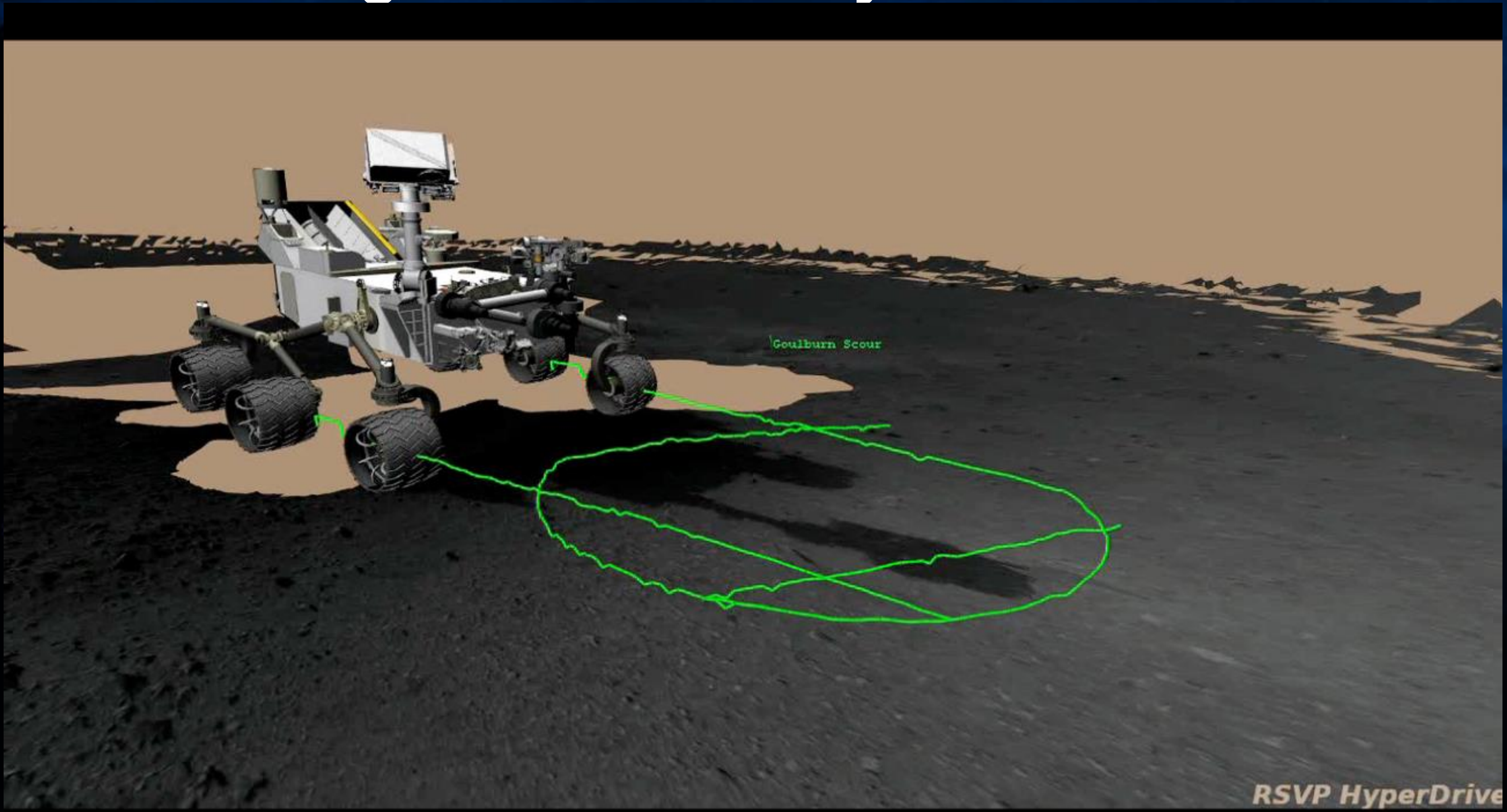
3D data from Navcam stereo is often supplemented by color texture information in Mastcam images

Multiple Drive Views



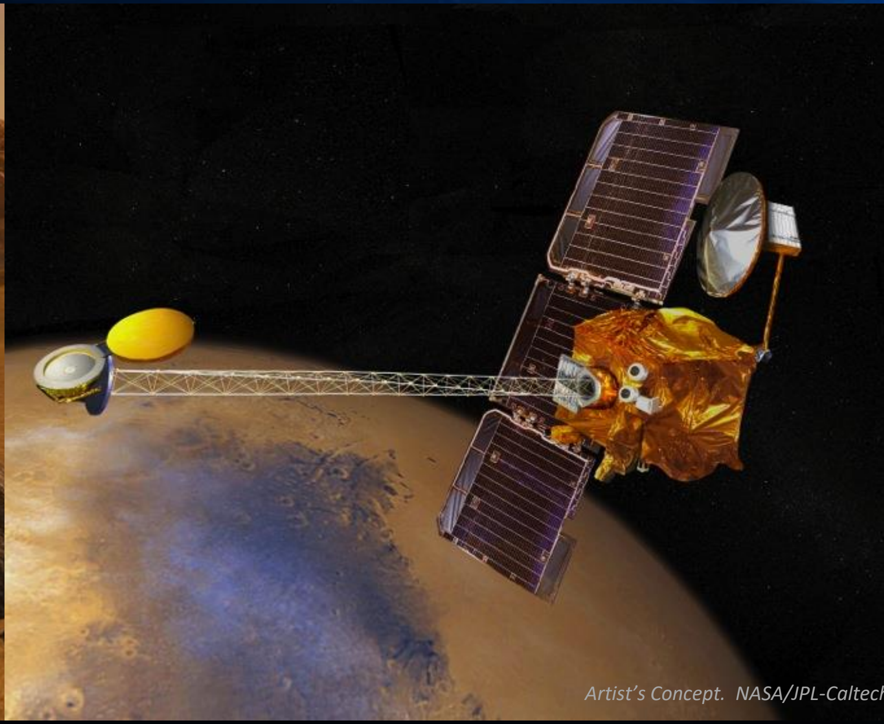
Drives are simulated on 3D meshes, and can be visualized in many ways. Here a mosaic of Navcam and Mastcam images provide context.

For “directed driving,” drivers command the rover to move a certain distance over ground that they know is safe.



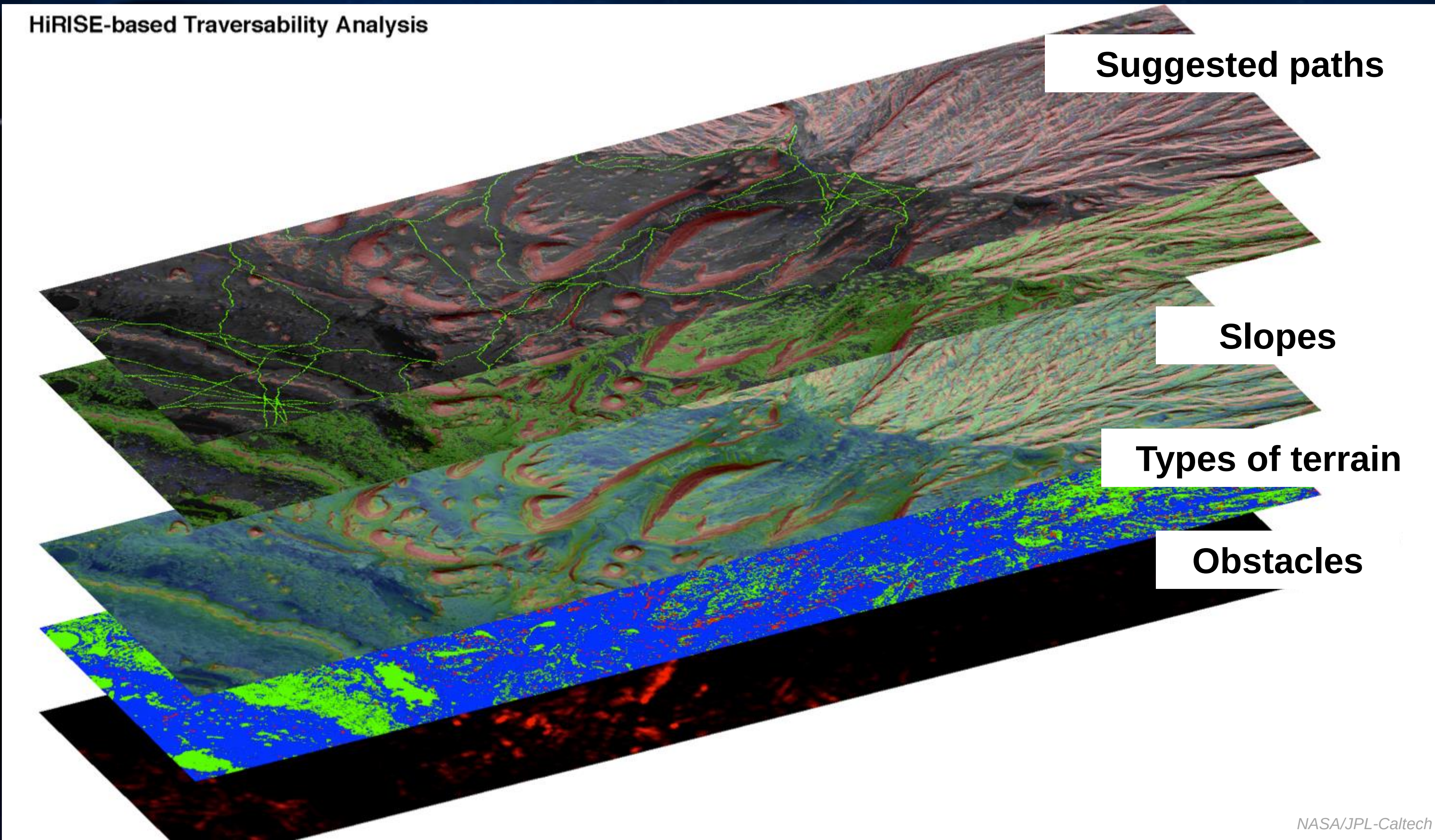
This is the fastest way to drive, because no predictive hazard processing is done, but distance is limited by what people can see. Curiosity will *always* stop the drive if a fault is detected!

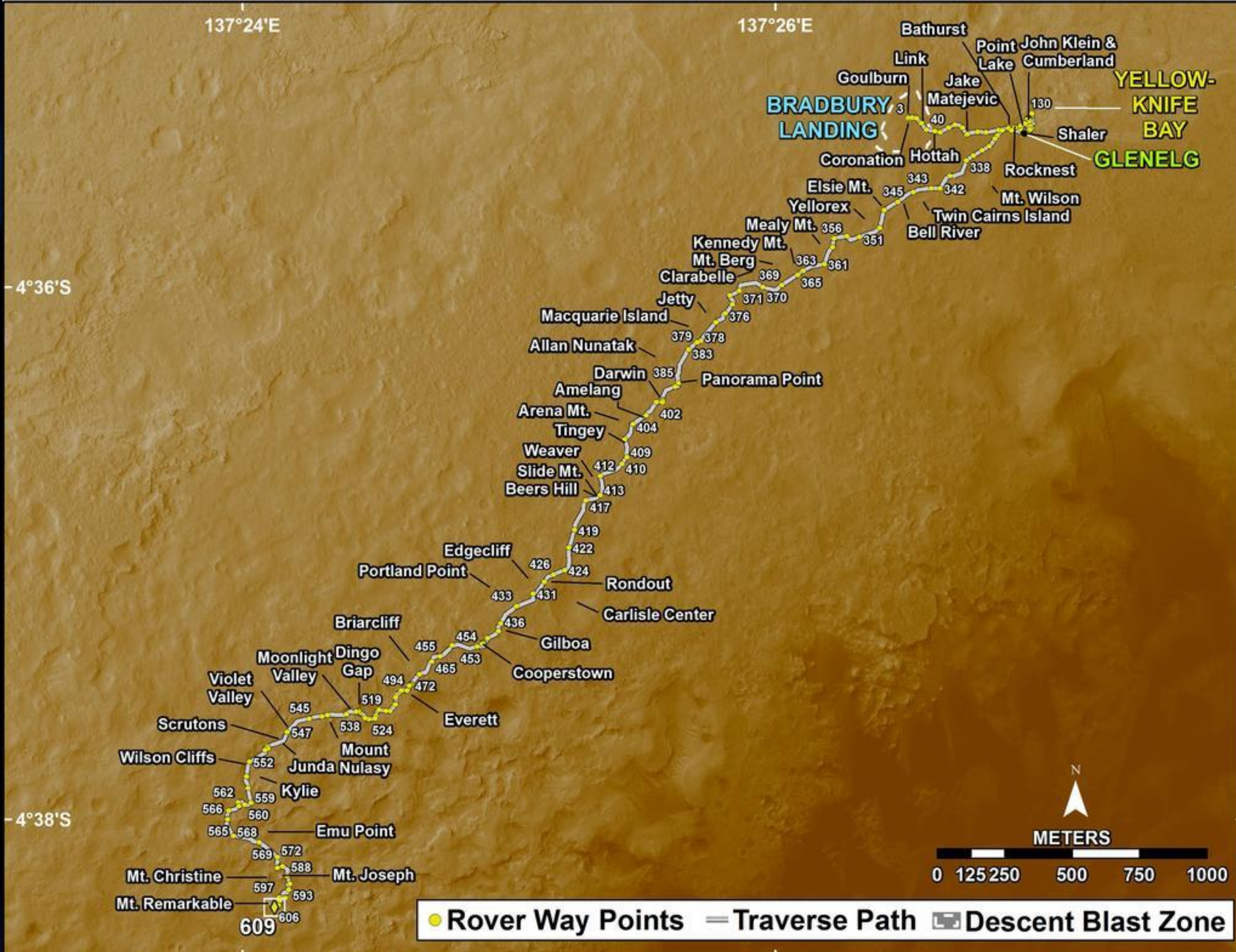
Curiosity carries out the activities and then sends data to the orbiters, whose larger antennas relay it to Earth.



It takes less energy and a smaller antenna to send data 200 miles (322 km) up to an orbiter, rather than millions of miles to Earth, though direct contact is available.

Data from the Mars Reconnaissance Orbiter helps “see” several kilometers ahead, allowing for long term planning.



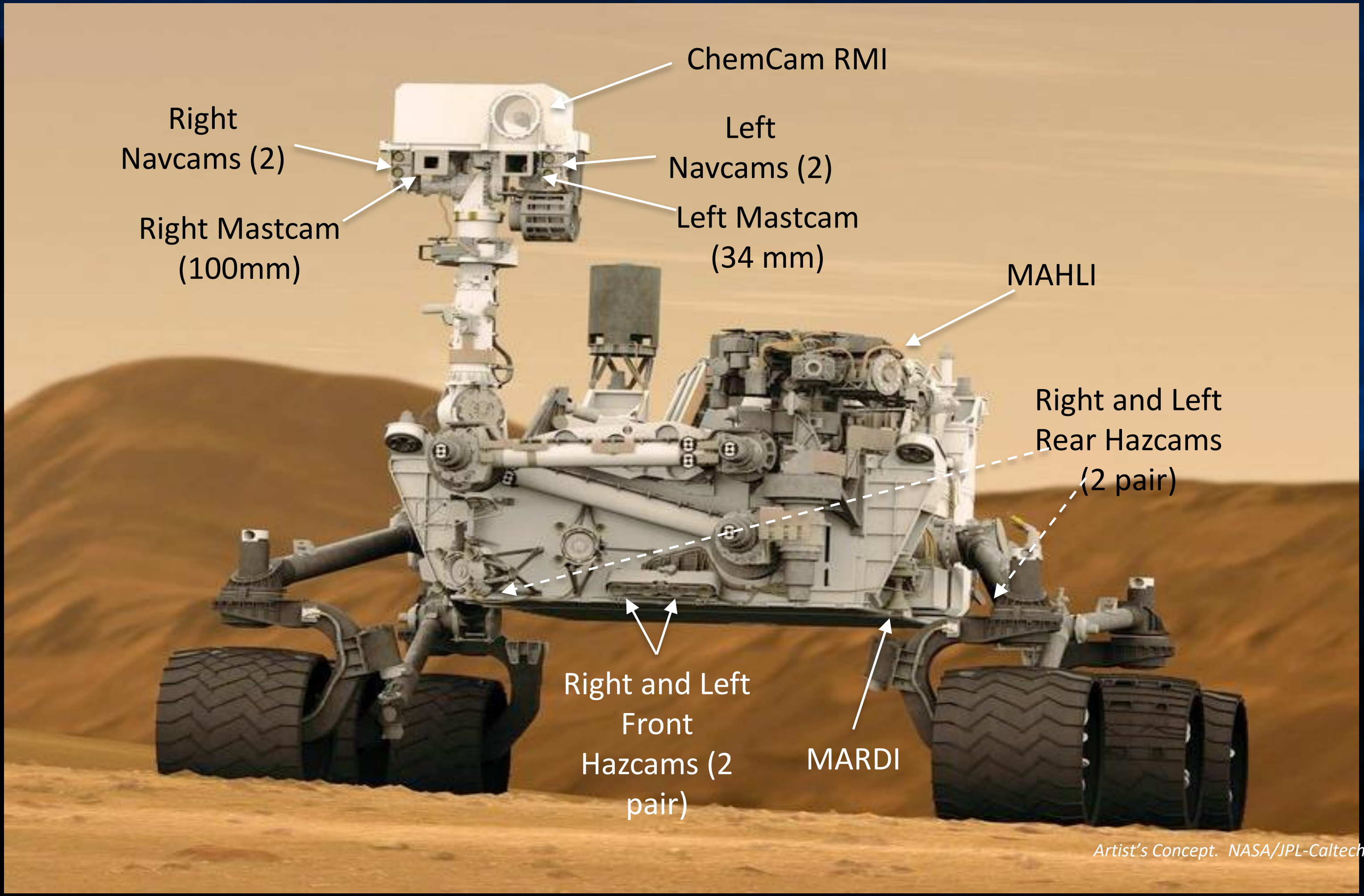

137°24'E
137°26'E
4°36'S
4°38'S
Bathurst
Point Lake
John Klein & Cumberland
Link
Goulburn
Jake Matejevic
YELLOW-KNIFE BAY
BRADBURY LANDING
Shaler
GLENELG
Coronation
Hottah
Rocknest
Elsie Mt.
Mt. Wilson
Yellorex
Twin Cairns Island
Bell River
Mealy Mt.
Kennedy Mt.
Mt. Berg
Clarabelle
Jetty
Macquarie Island
Allan Nunatak
Darwin
Panorama Point
Amelang
Arena Mt.
Tingey
Weaver
Slide Mt.
Beers Hill
Edgecliff
Portland Point
Rondout
Carlisle Center
Briarcliff
Gilboa
Moonlight Valley
Dingo Gap
Cooperstown
Violet Valley
Everett
Scrutons
Mount Nulasy
Junda
Wilson Cliffs
Kylie
Emu Point
Mt. Christine
Mt. Joseph
Mt. Remarkable
609
METERS
0 125 250 500 750 1000
Rover Way Points
Traverse Path
Descent Blast Zone

WDC? Robotics Tech!

Velocity-controlled Driving
Autonomous Fault Response
Visual Odometry
Dense Stereo Vision
Autonomous Terrain Assessment
Local and Global Waypoint Planning
Multi-sol Driving
Visual Target Tracking
Precision Arm Placement
Percussive Drill
Cached Sample Manipulation
Simulation
Rover Sequencing and Visualization

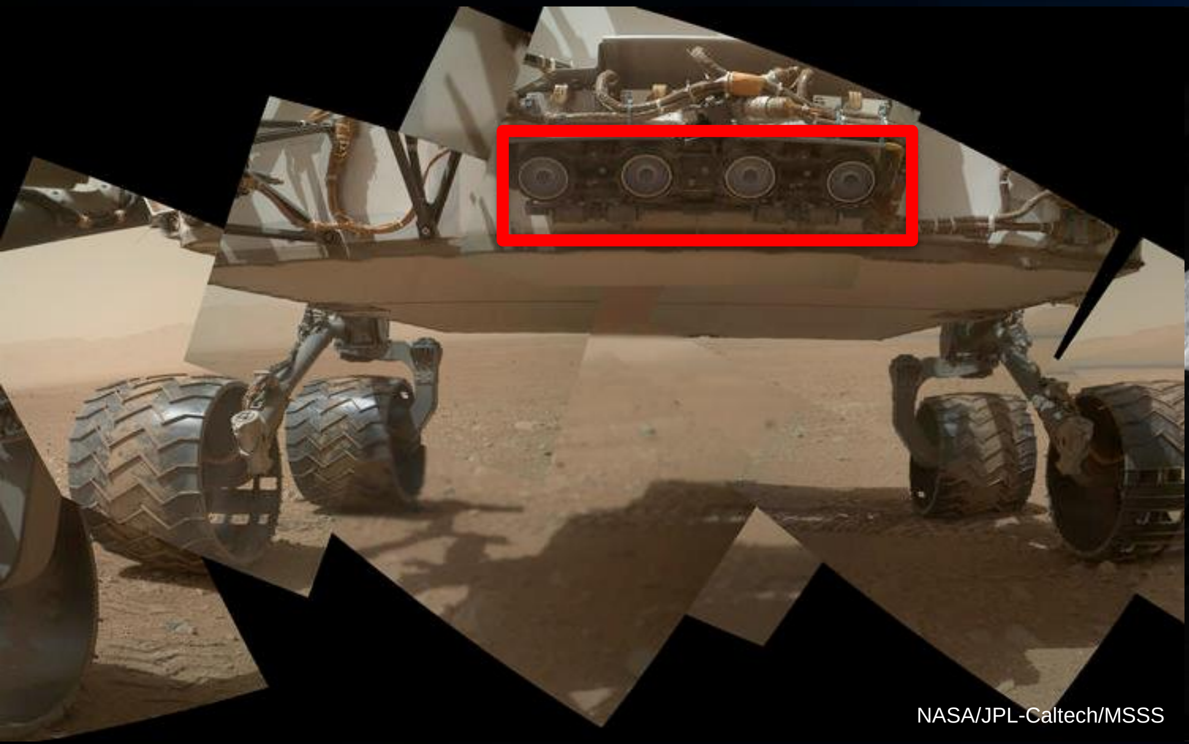
Artist's Concept. NASA/JPL-Caltech

Curiosity has 17 cameras

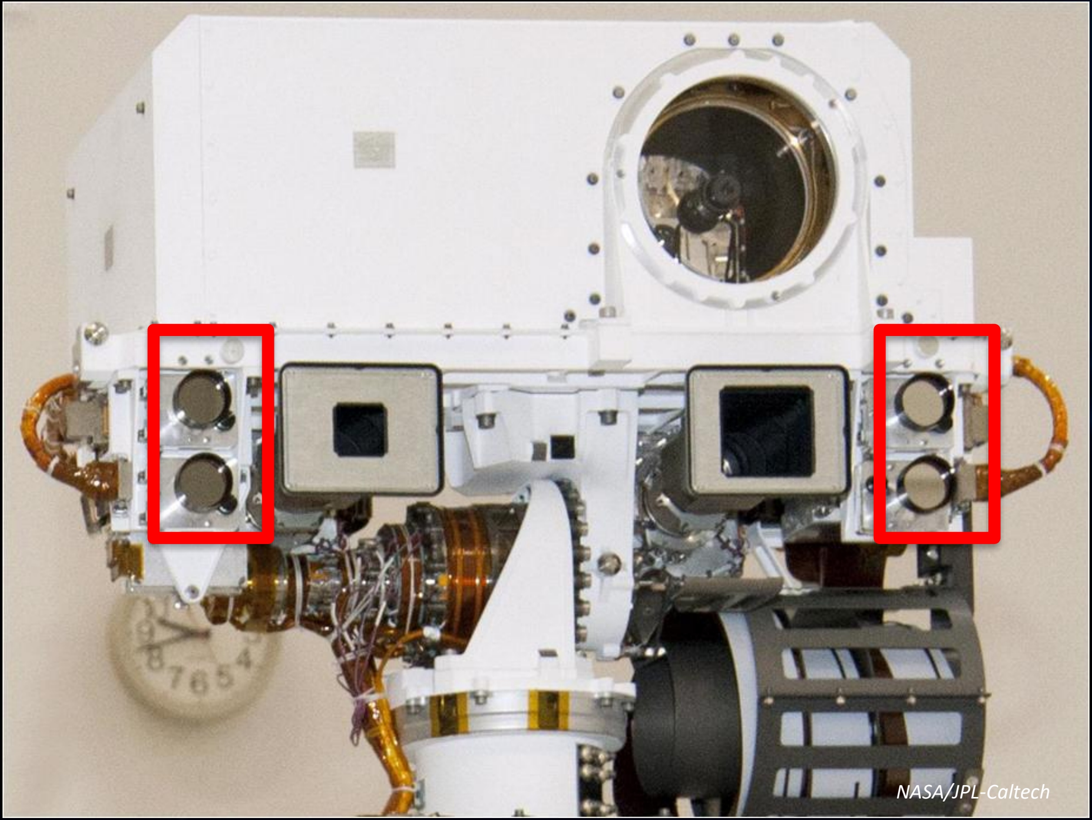


However, only the Hazcams and Navcams are tied into the auto-nav software.

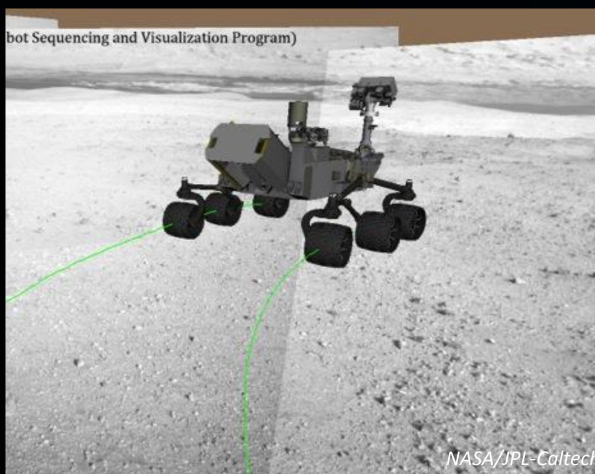
The hazard avoidance cameras give a 120º wide angle view of the area near the rover. Front cameras have 16cm baseline, rear cameras have 10cm baseline.



The 45º navigation cameras are almost 7 feet off the ground with 42cm baseline, providing good views over nearby obstacles or hills and into ditches.

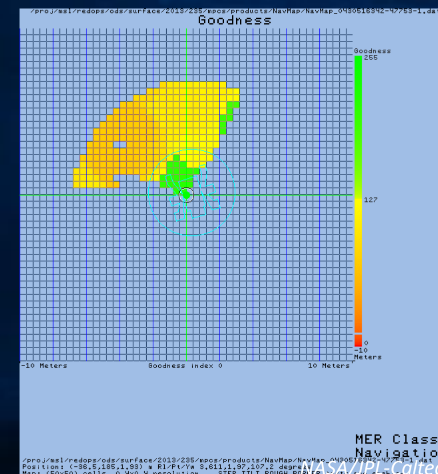


Human Rover Drivers Decide How Much Autonomy is Desired Based on Terrain and Available Resources



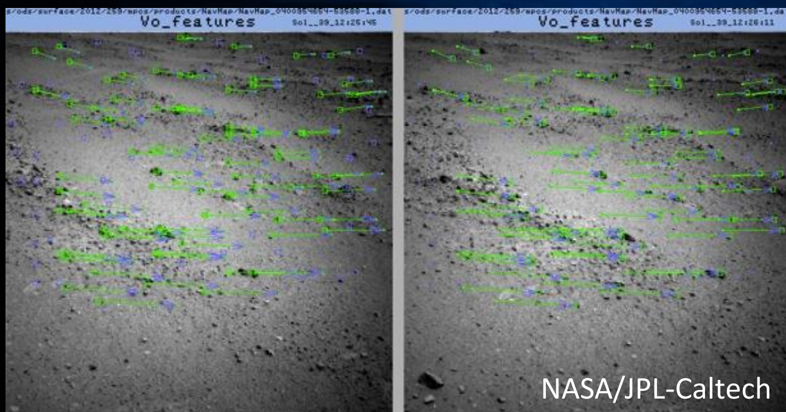
Directed driving

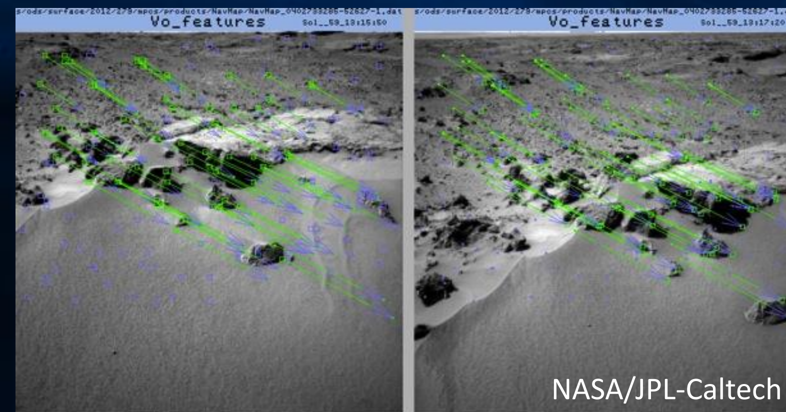
Visual odometry, or Slip Check + "Auto"

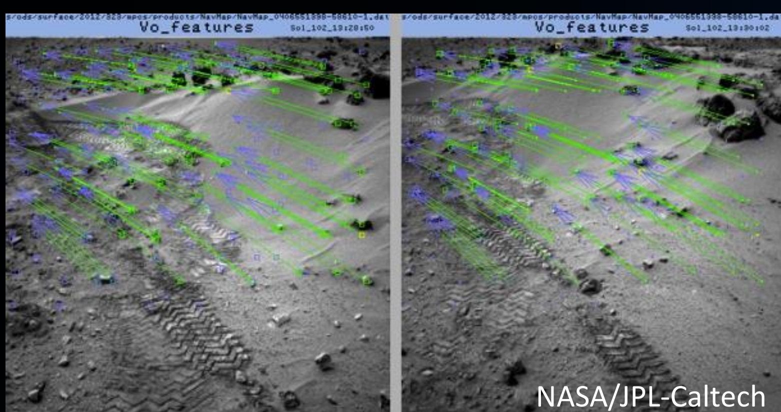


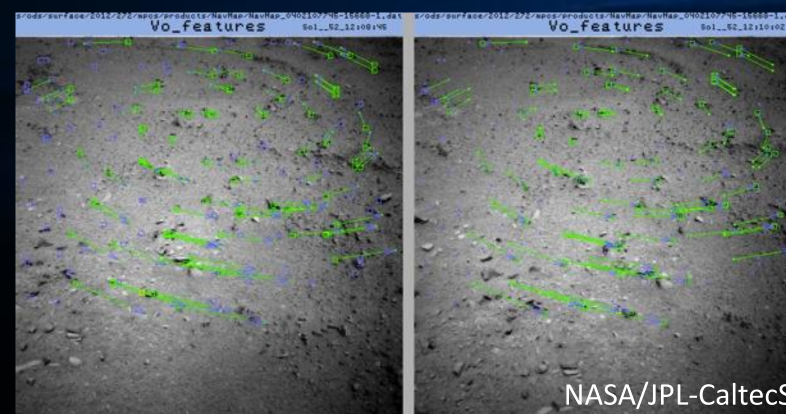
Auto-navigation; Geometric Hazard Detection and Avoidance

Using visual odometry, the rover constantly compares pairs of images of nearby terrain to calculate its position.



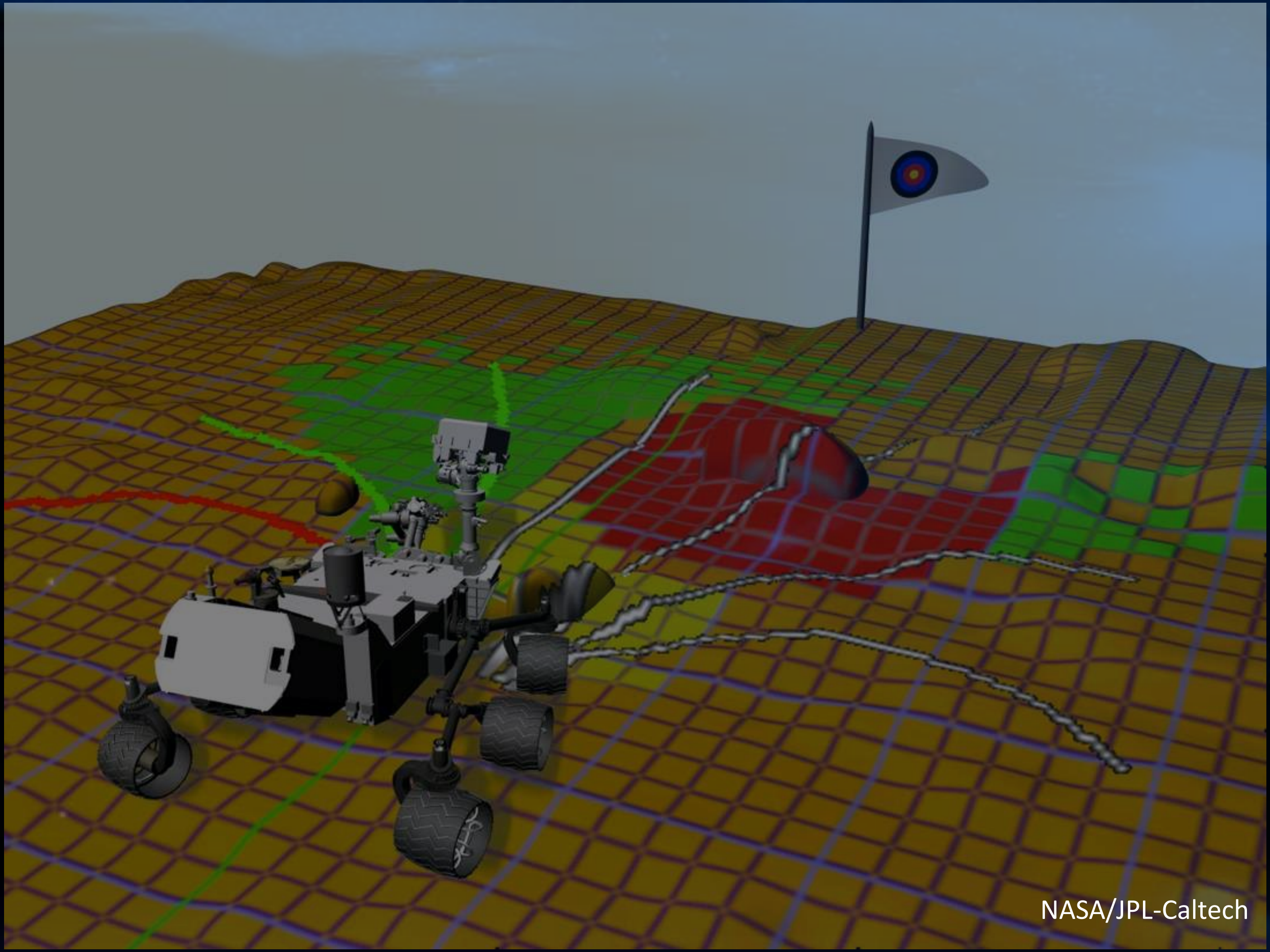






Unlike terrestrial robots, Curiosity drives as far as possible between VO images

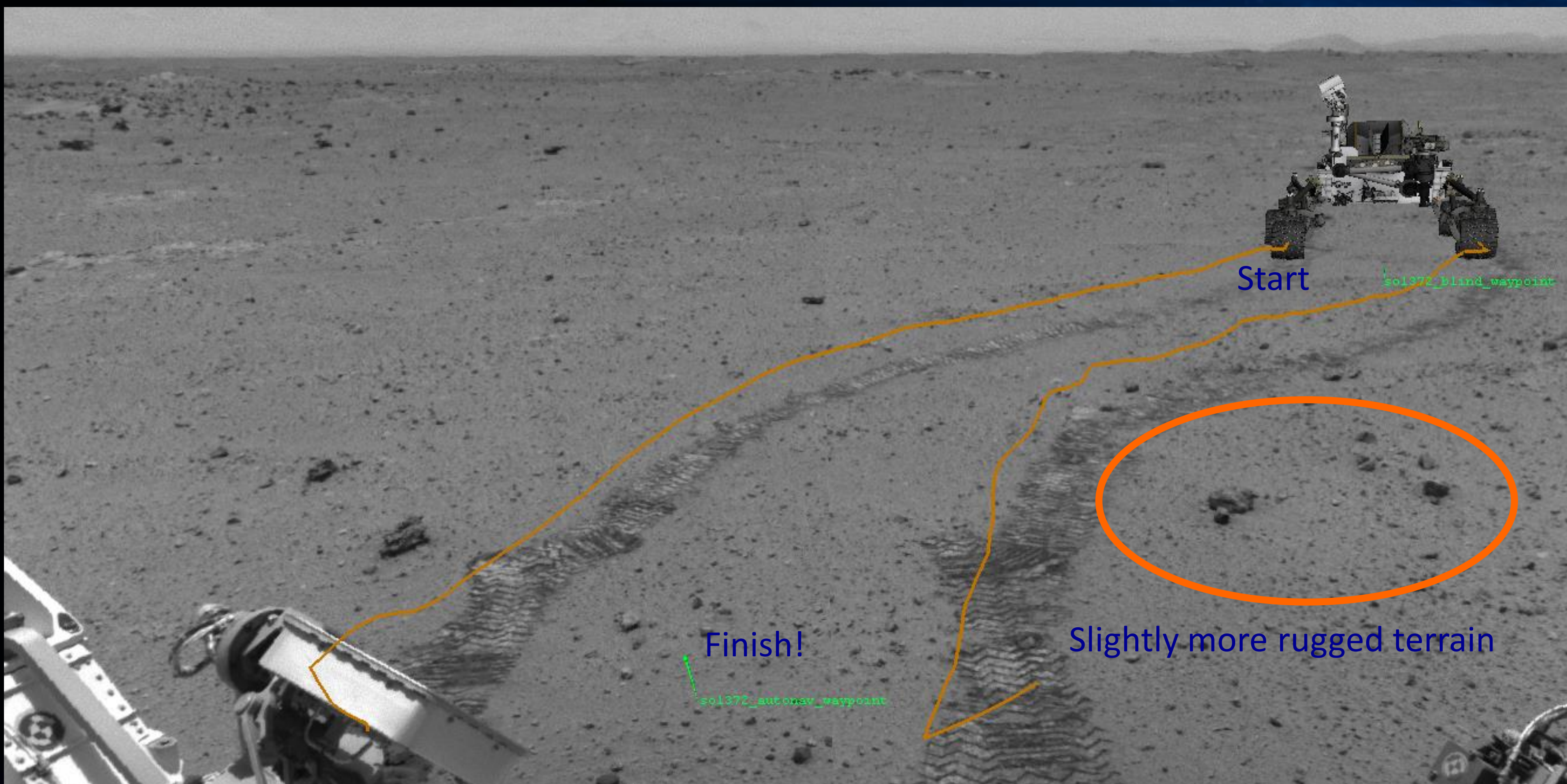
Human drivers *and* Curiosity depend on 3D image analysis to find the safest path.



During nominal auto-nav, the rover stops every 0.5-1.5 meters, takes 4 sets of images, evaluates hazards, and then chooses where to drive.

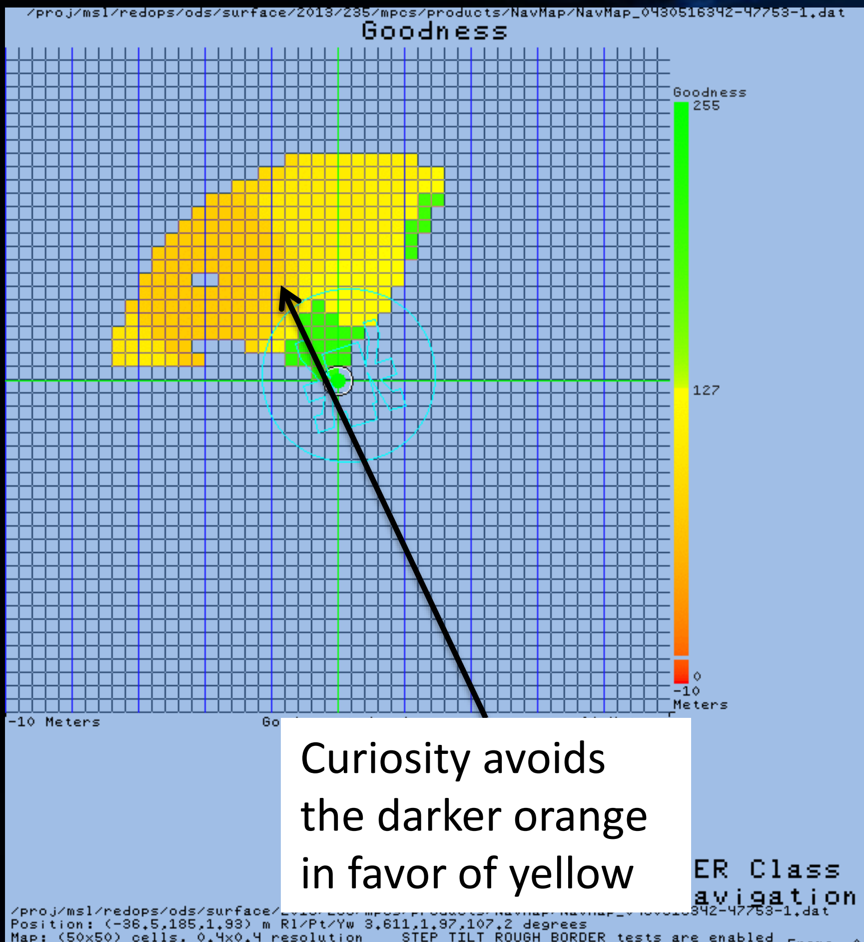
Auto-nav extends directed drives into previously unseen terrain

Wheel tracks after the first auto-nav drive on sol 372 show that Curiosity chose to drive around a little mound of loose rock.

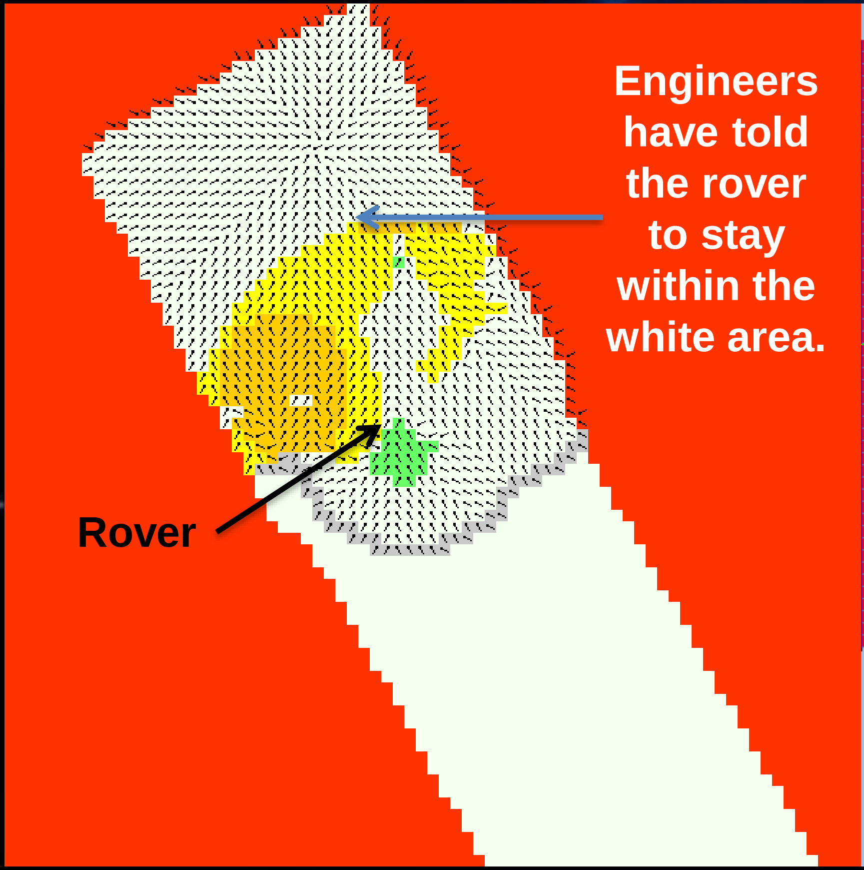


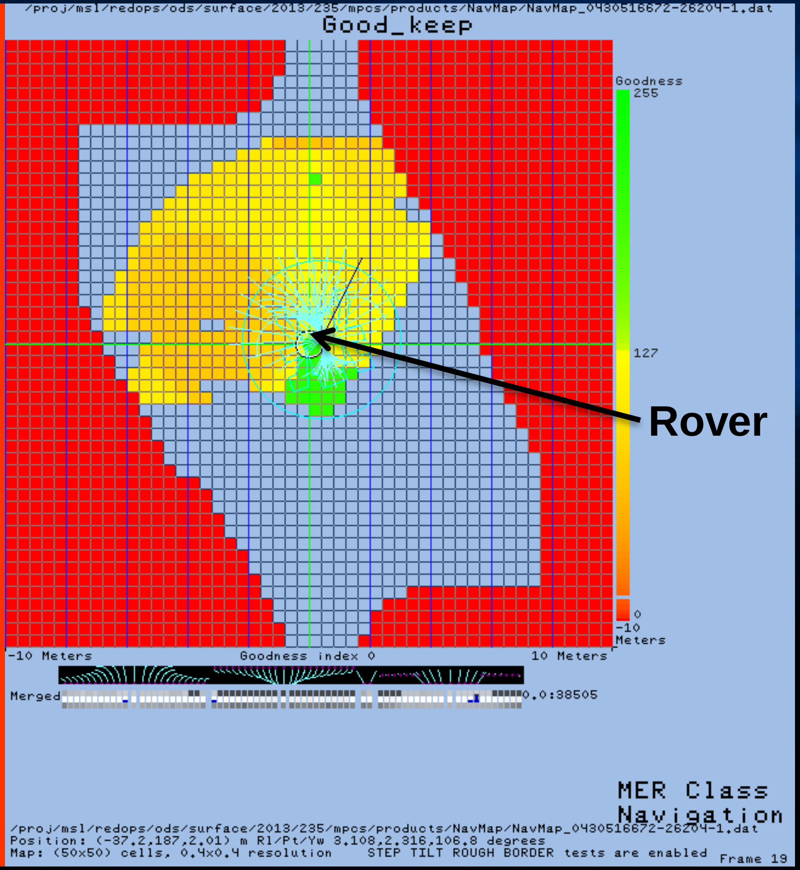
[redacted]

Curiosity's map and tracks show this decision to turn was based on her evaluation of the terrain.



The rover reduces a stereo point cloud into a configuration space, labeling unsafe areas red and safe areas green.





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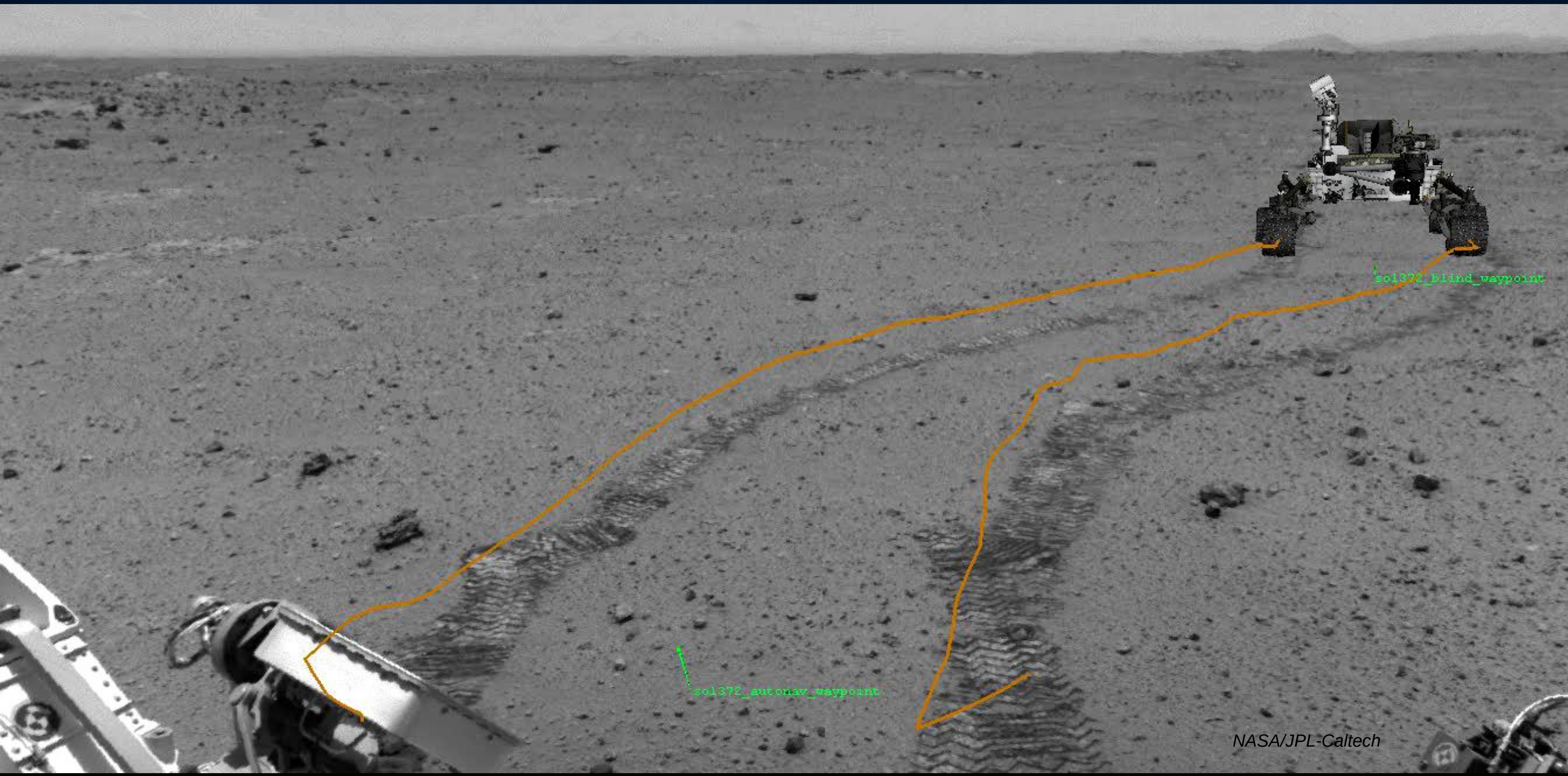
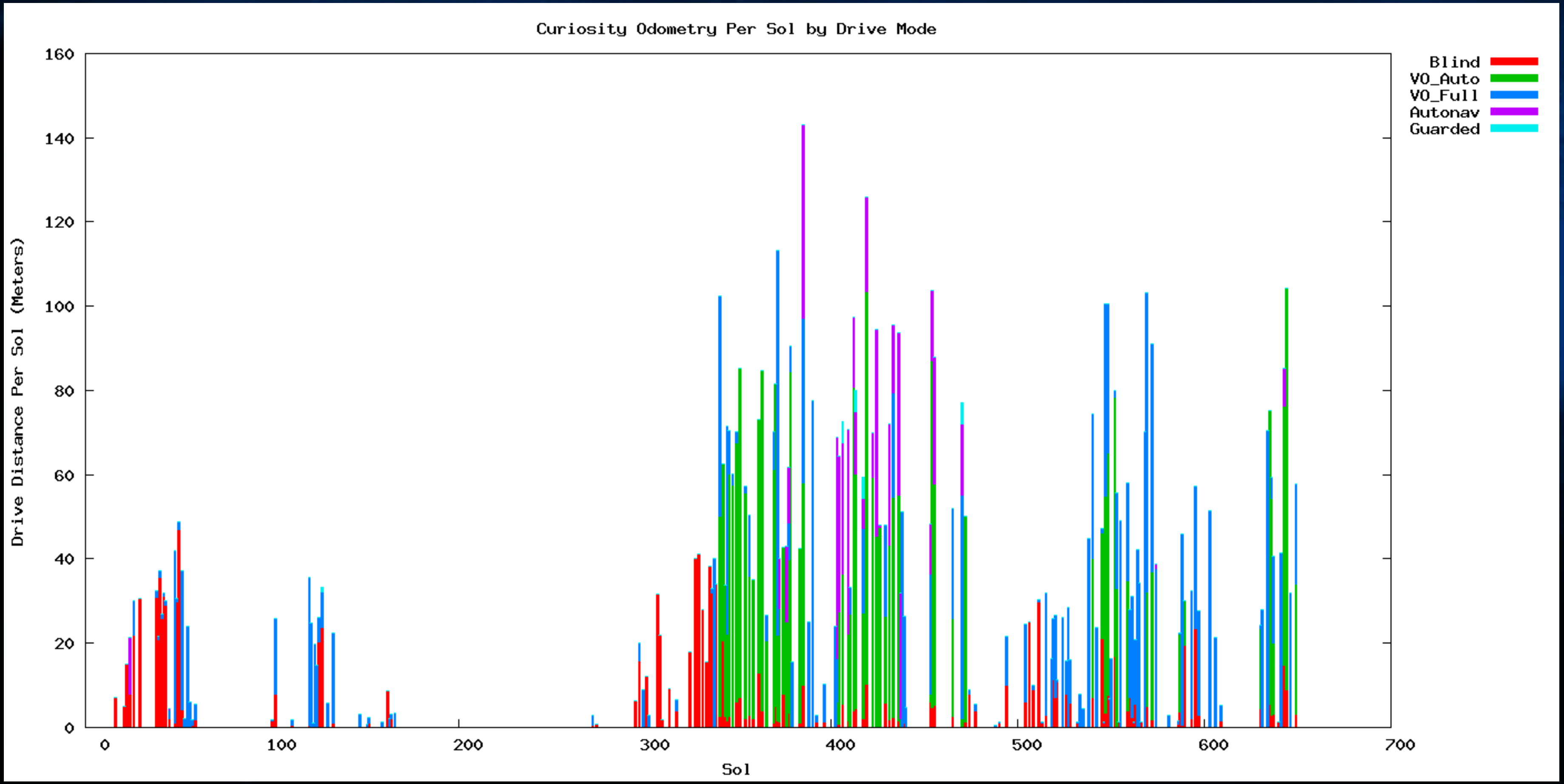
Yellow means drive carefully, just like on Earth.

Animation of Curiosity's actual Sol 372 drive over a picture of her tracks

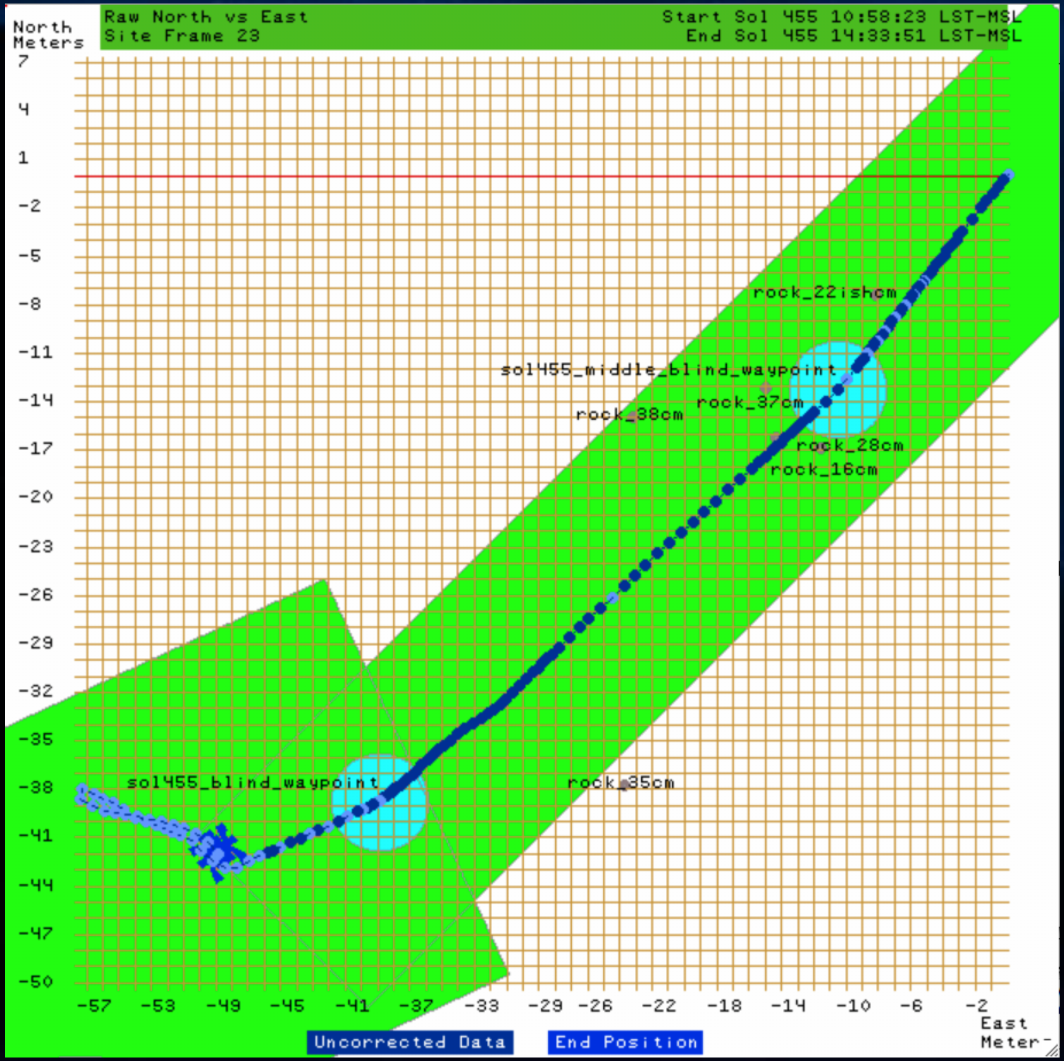


Finish!

Curiosity Odometry Per Sol



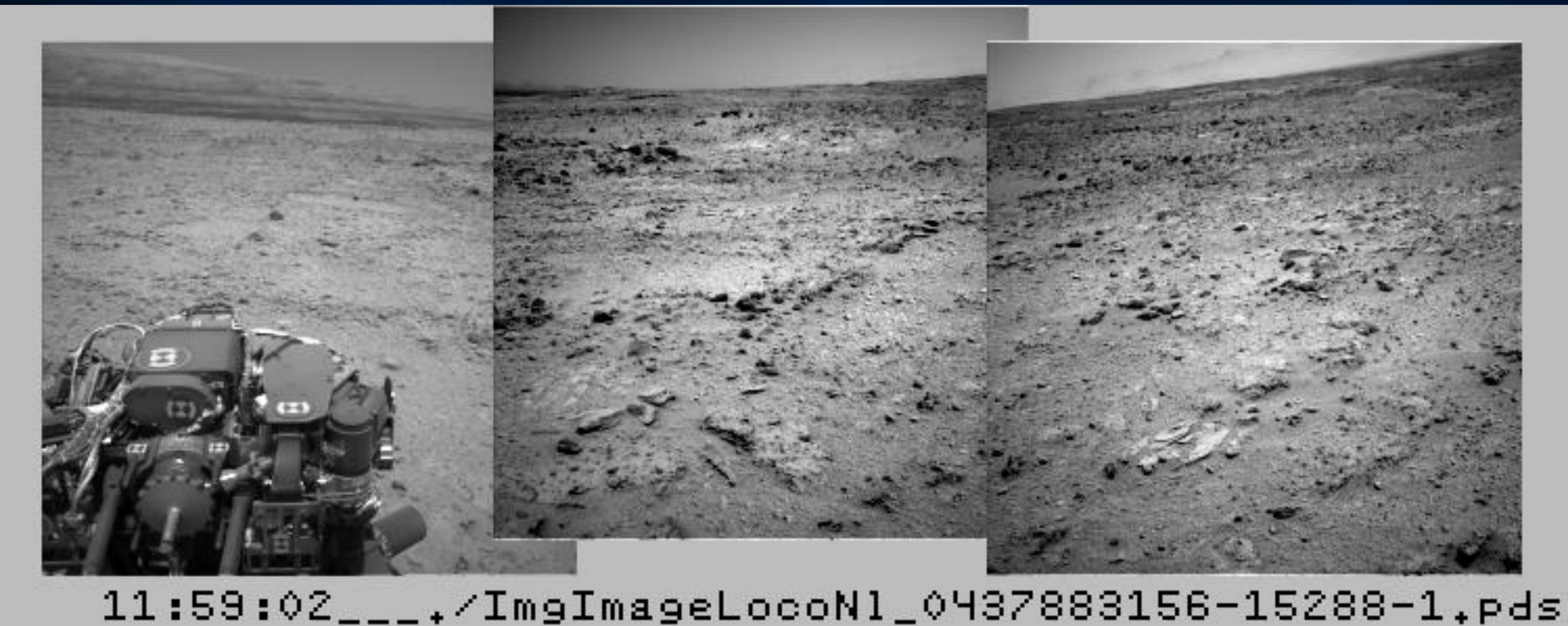
On sol 455, Curiosity encountered a small crater and began to drive around it



Small light blue dots represent the imaging steps

NASA/JPL-Caltech

A Rover's-eye view of the Autonomous Portion of the sol 455 drive



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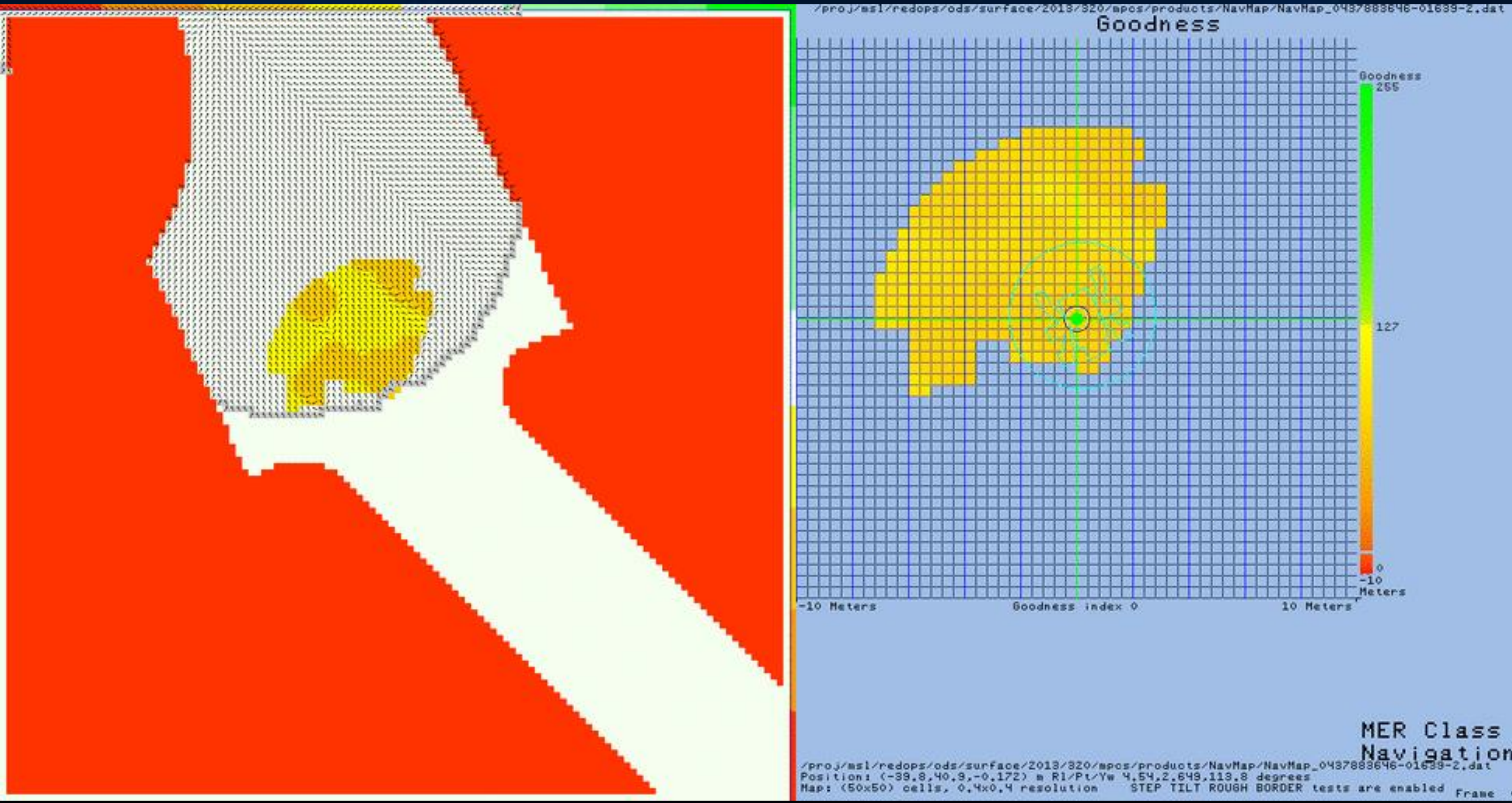
Then, boxed in by Keepin Zones, D* tried backtracking!



[redacted]

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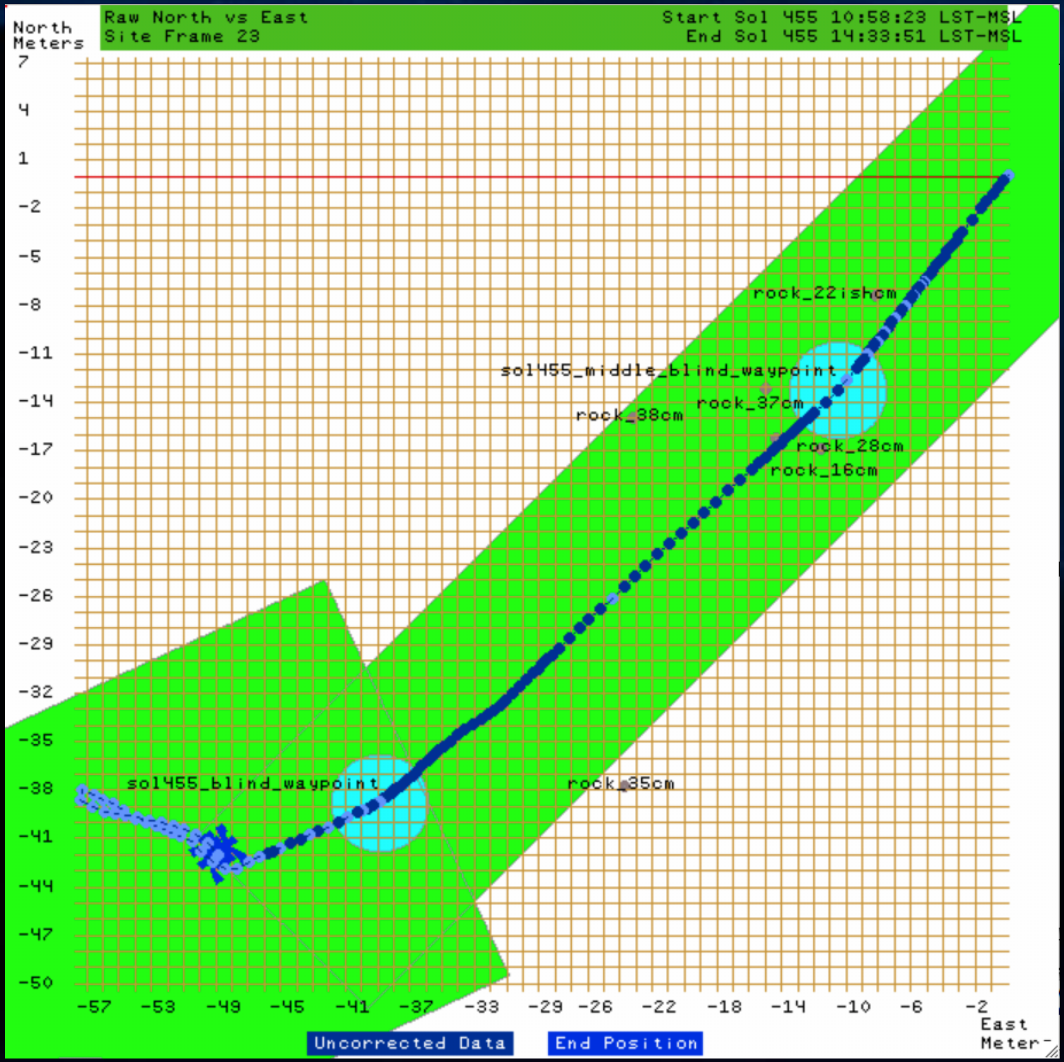
On sol 455, Curiosity encountered a small crater and began to drive around it



Small light blue dots represent the imaging steps

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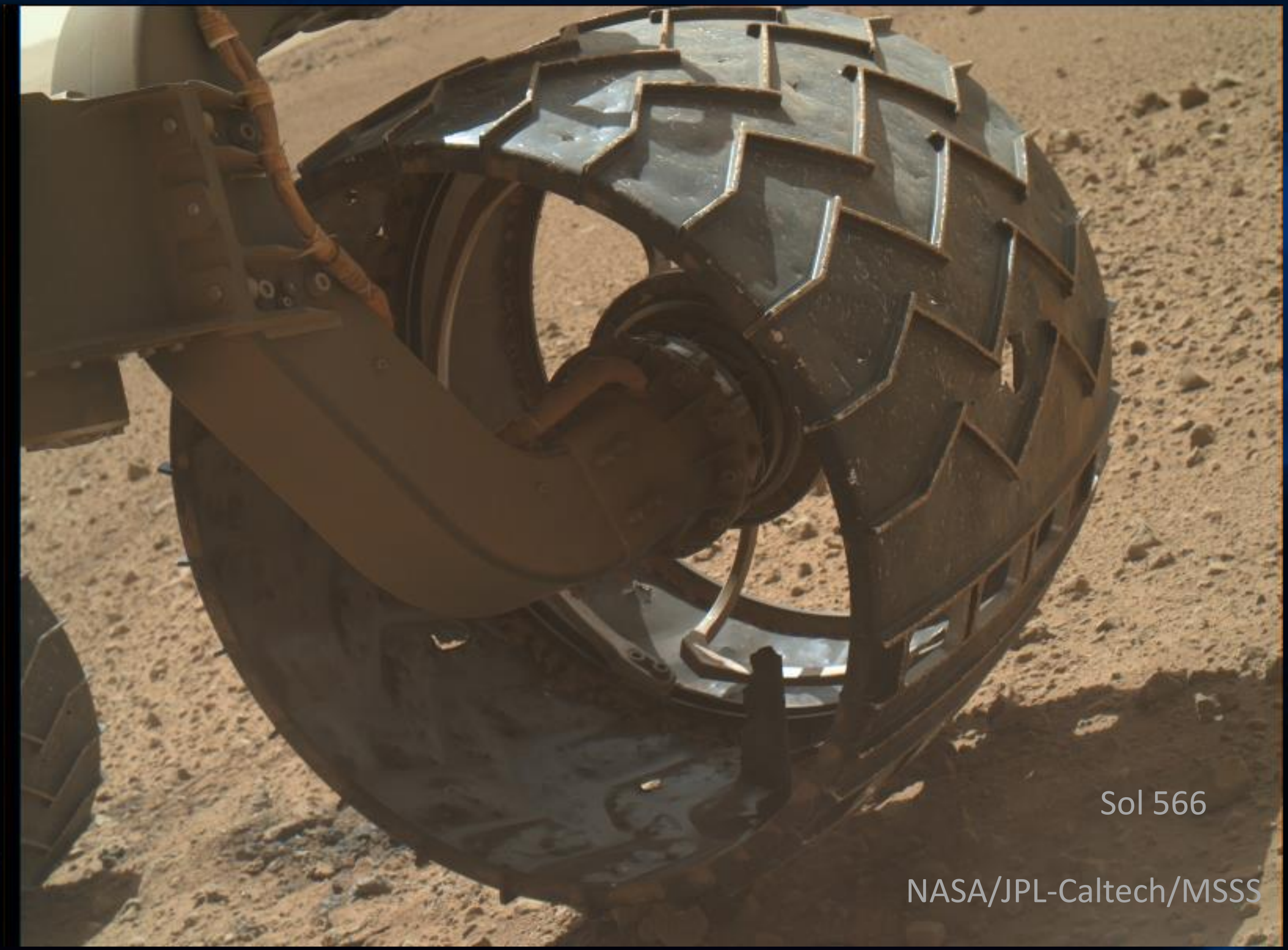
Sol 465: Wheel Wear

- We started to notice unusual amount of wear in our wheels



Sols 15-59: Before and After

Sol 15

Sol 60

Minor denting by small sharp rocks

Sols 60-309: Before and After

Sol 60

Sol 296

(No driving between sols 60-99, sols 167-271 and other smaller time windows)

[redacted]

Sols 313-396: Before and After

Sol 297

Sol 402

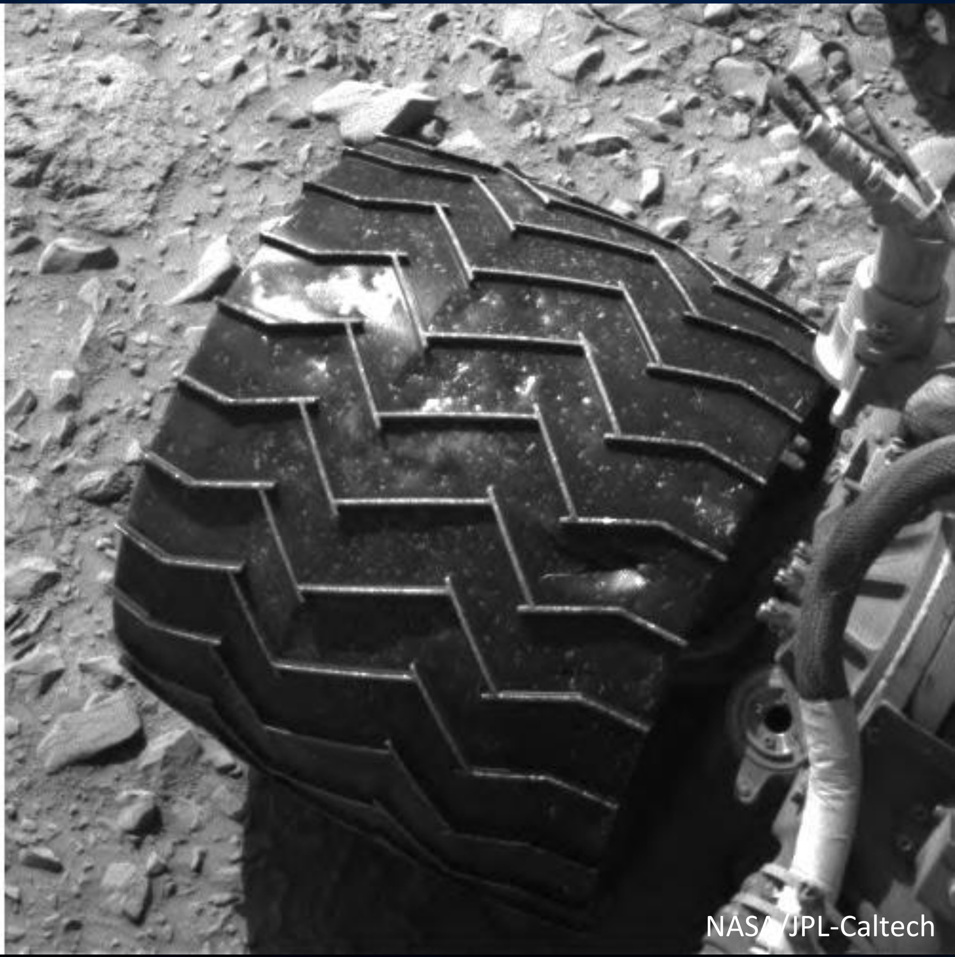
(No driving between sols 310-312 and sols 397-401;
Wheel in partial image at sol 313 looks like that at sol 297)

[redacted]

Sols 402-477: Before and After

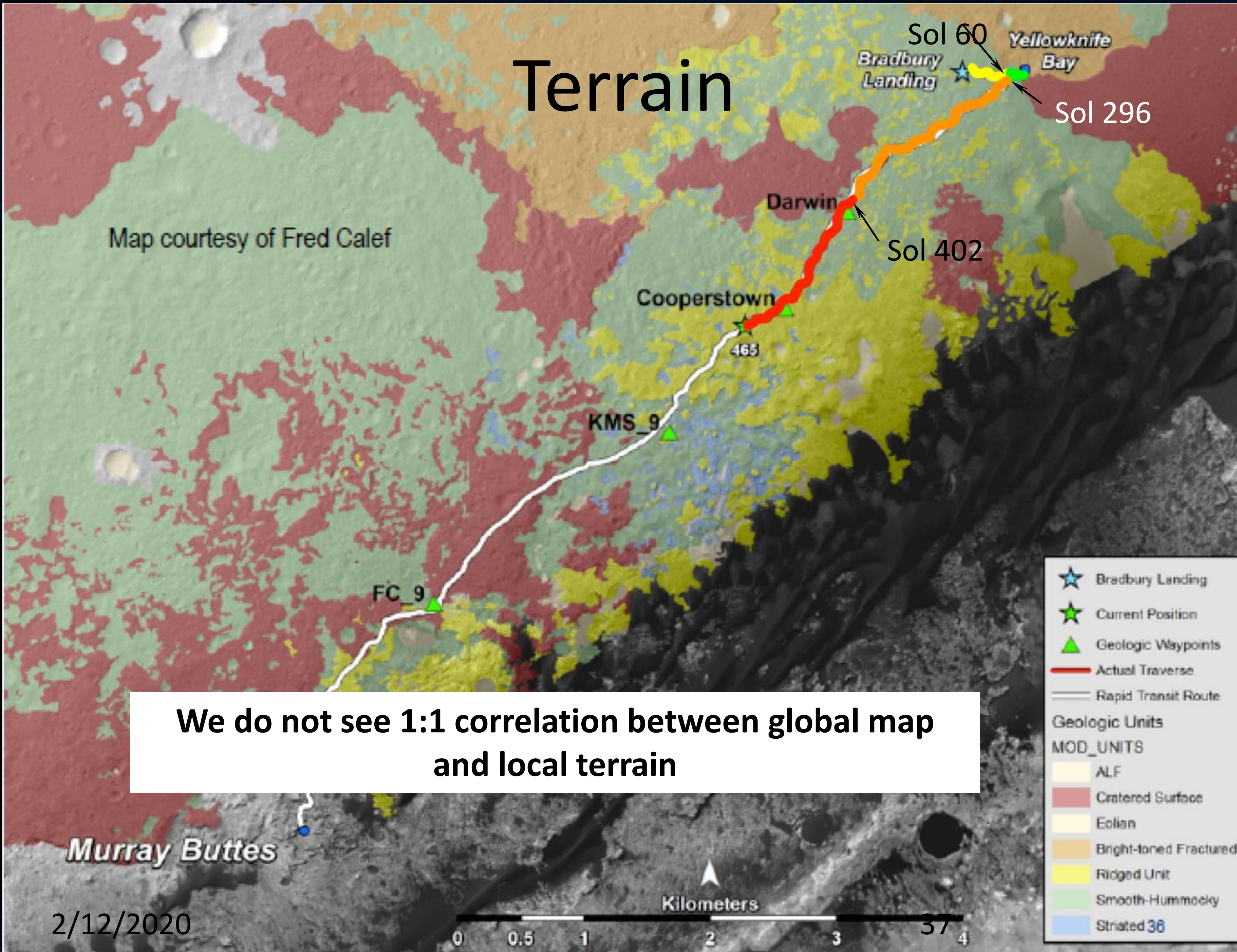
Sol 402

Sol 477



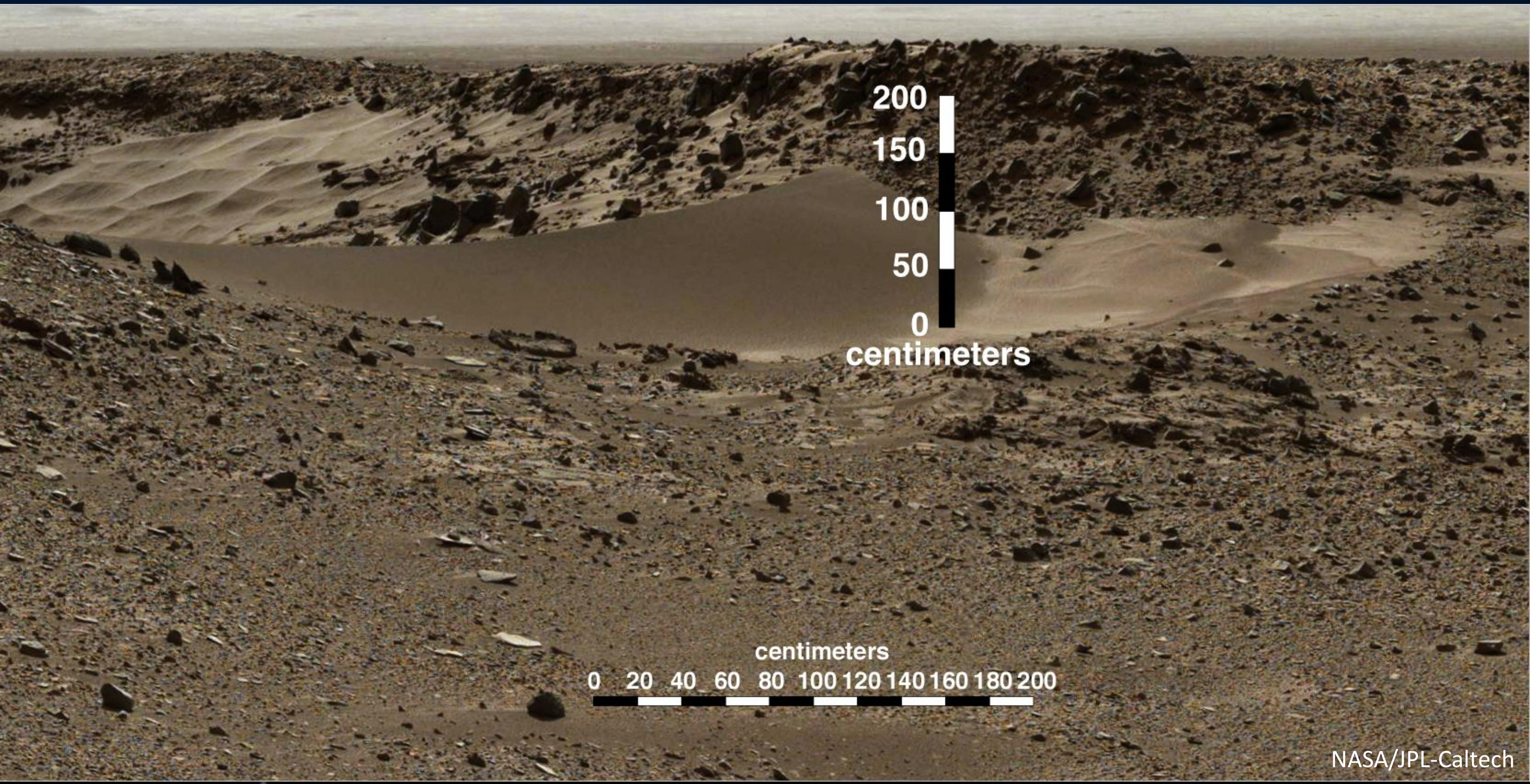
Severe denting by grouser-sized rocks

Terrain

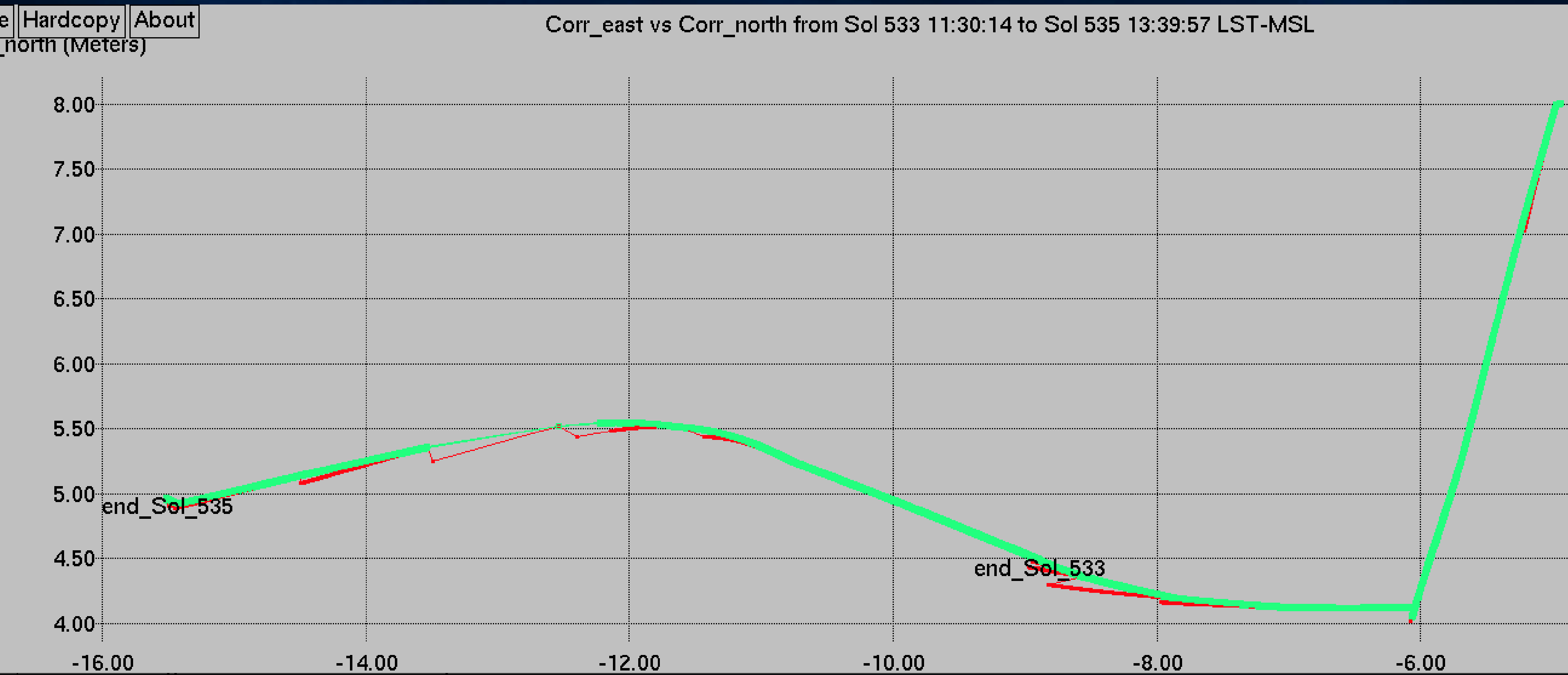


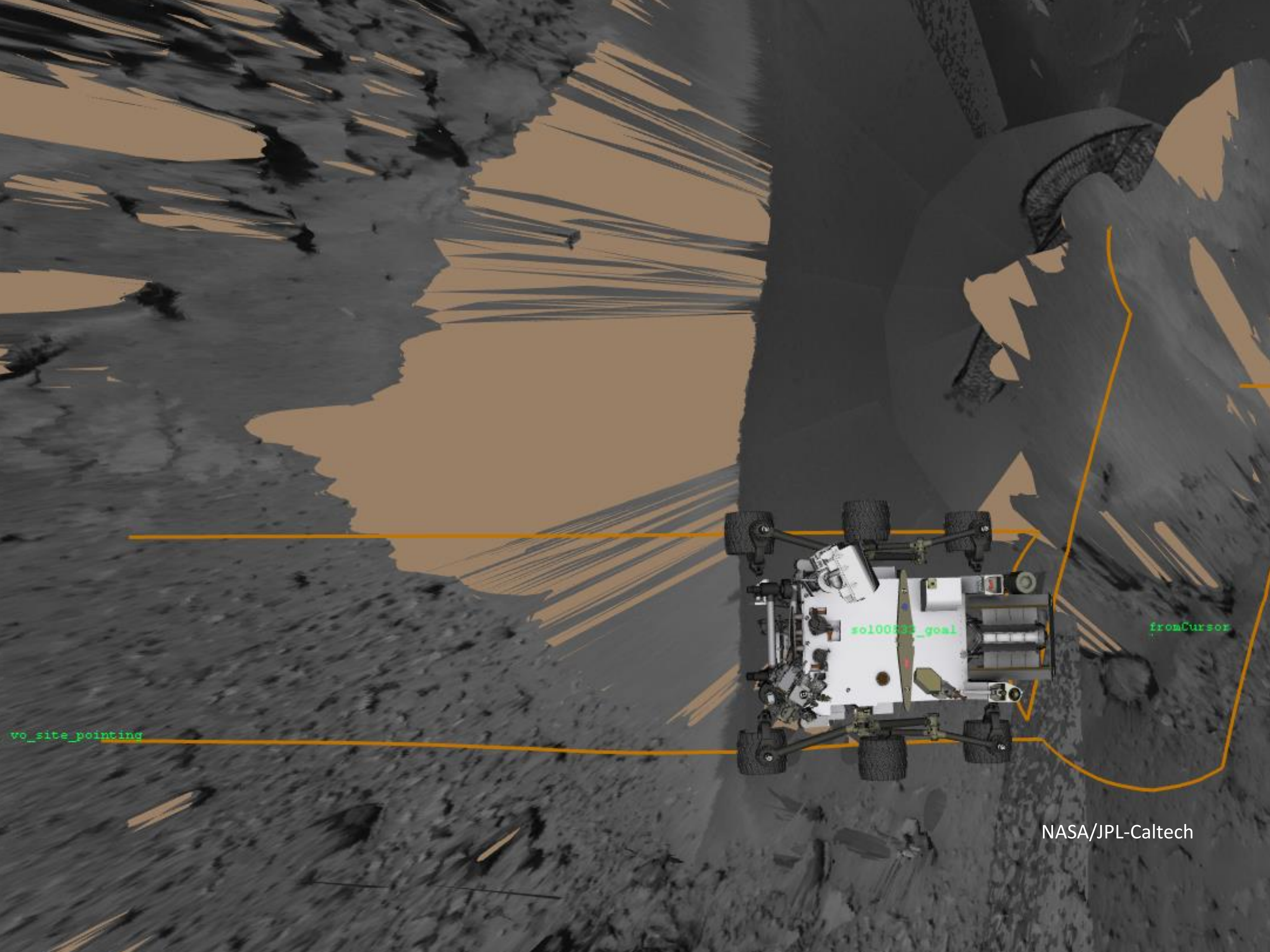
We do not see 1:1 correlation between global map and local terrain

Sol 533-535: Dingo Gap



Sol 533-535: Dingo Gap





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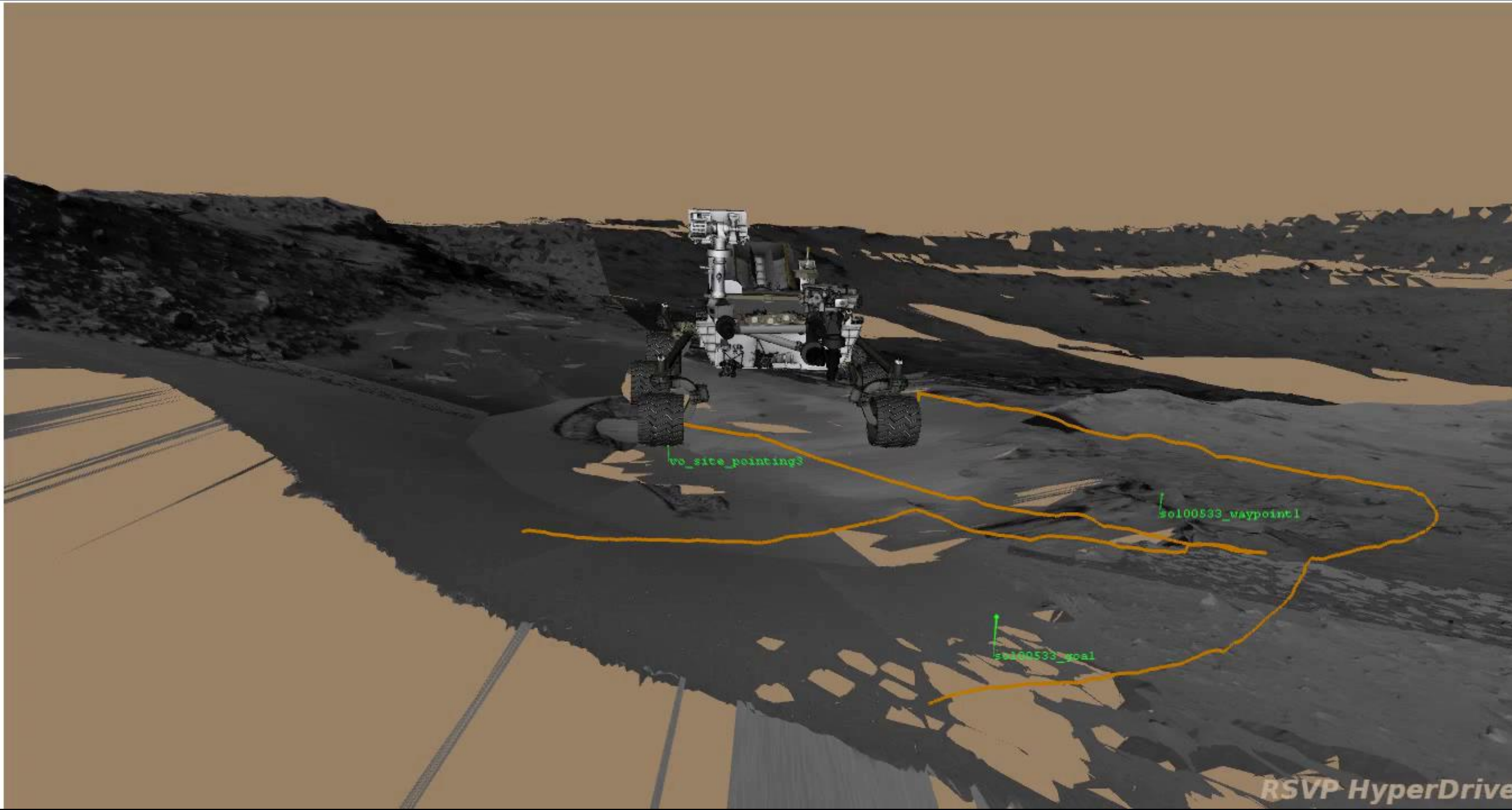
Sol 535: Climbing Over



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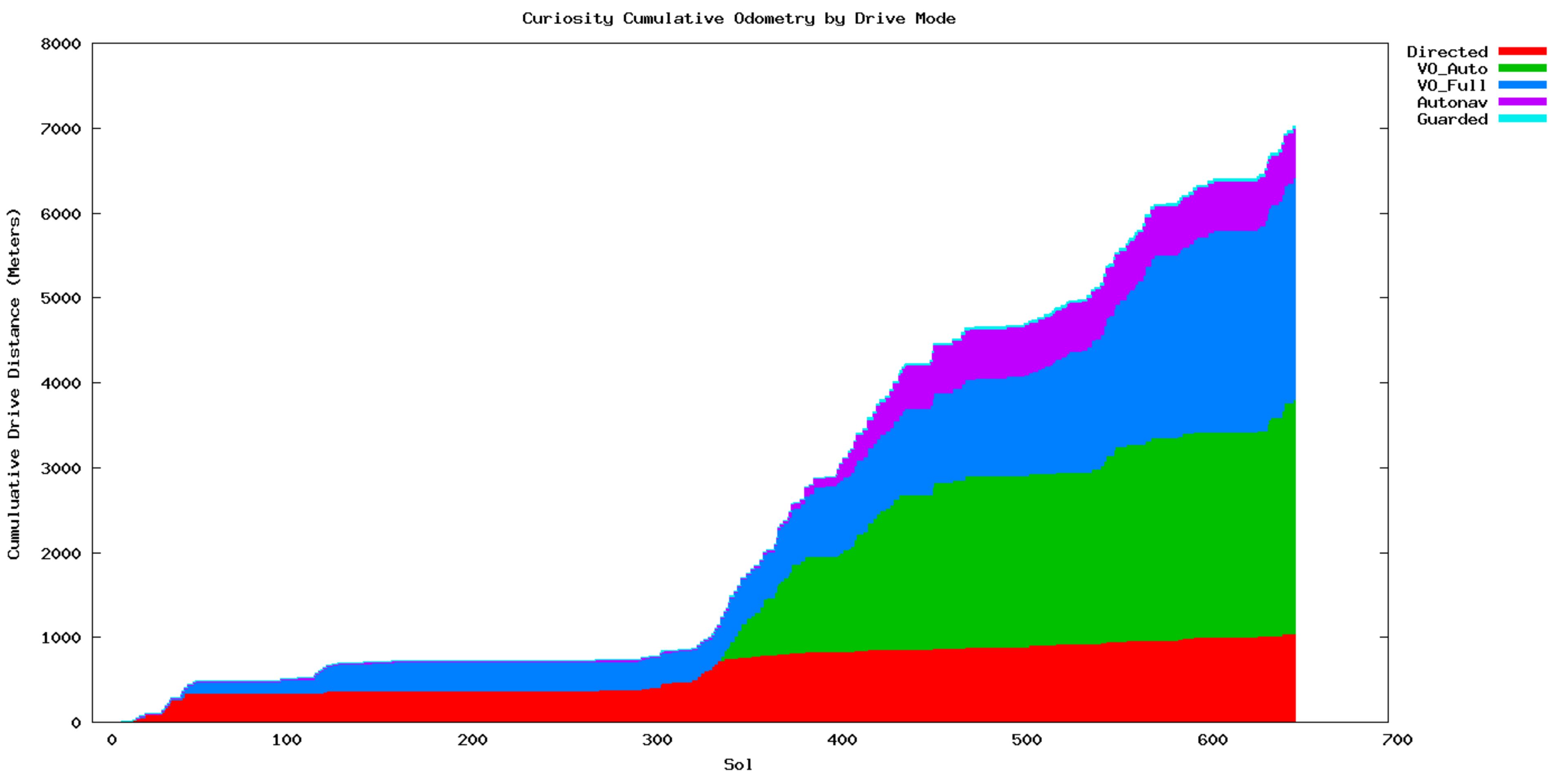
Sol 533-535: Dingo Gap

Curiosity Cumulative Odometry



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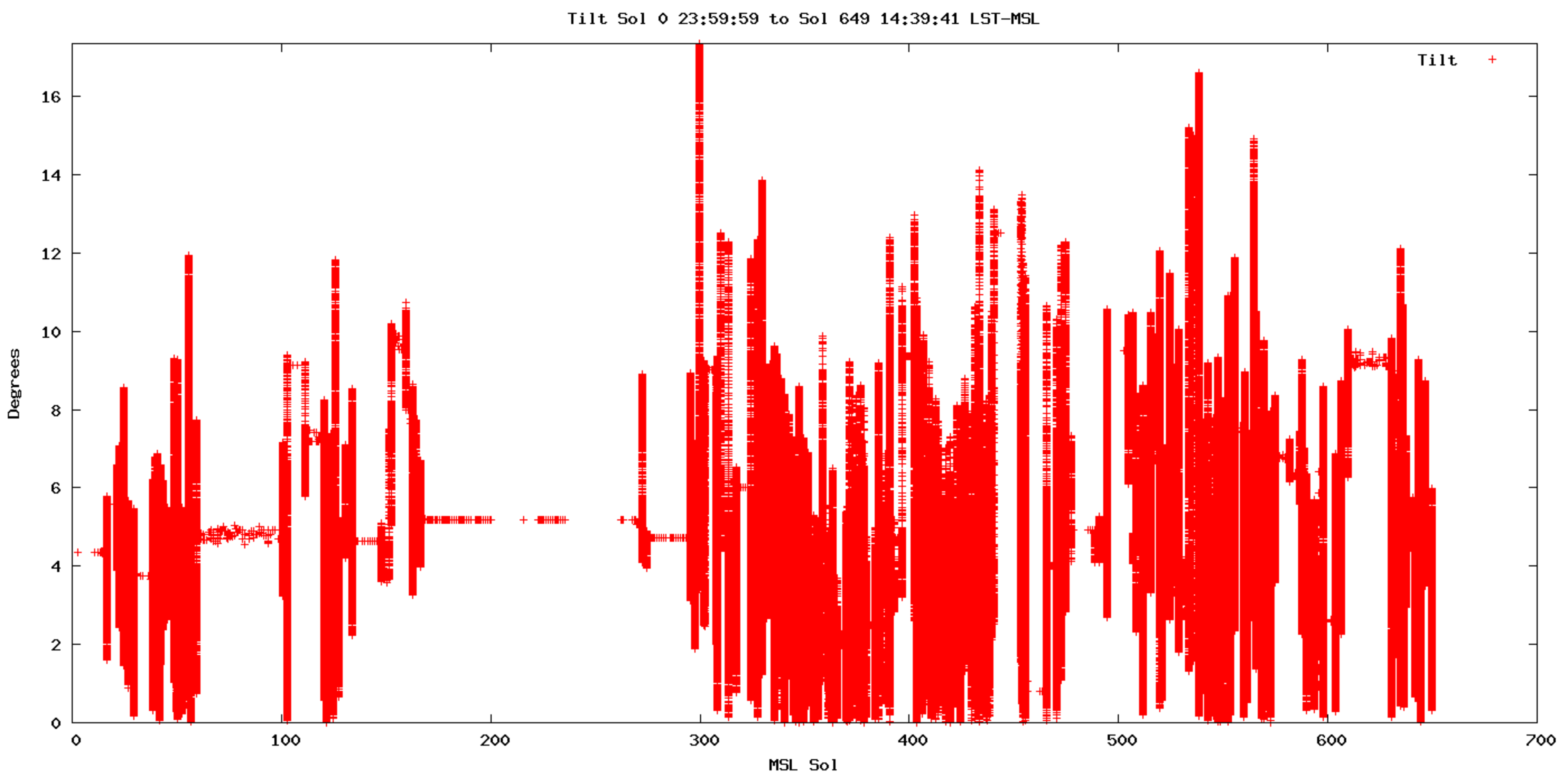
Curiosity Tilt Per Sol (through Sol 650)



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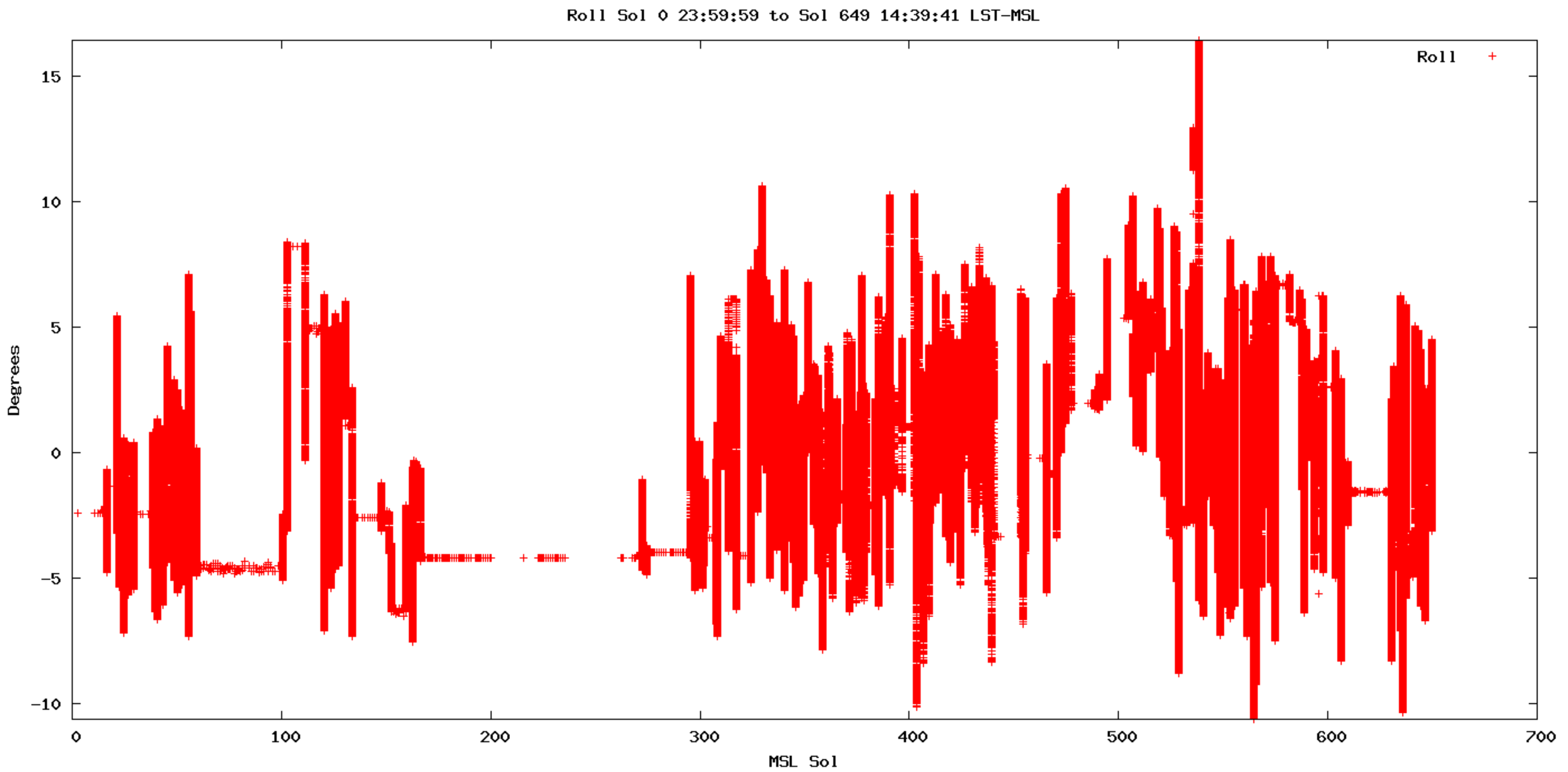
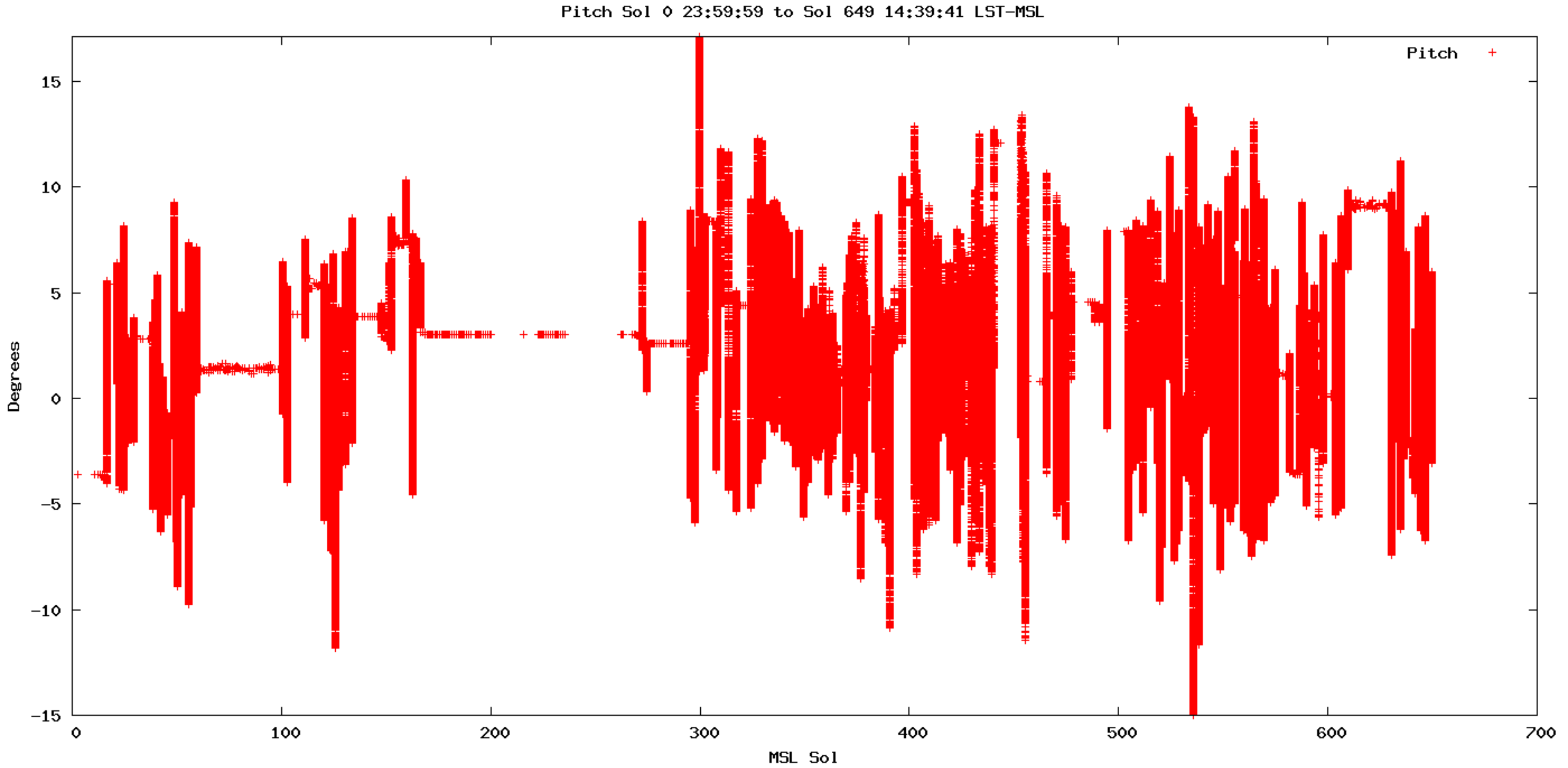
Curiosity Roll through Sol 650



NASA/JPL-Caltech

Curiosity Pitch through Sol 650



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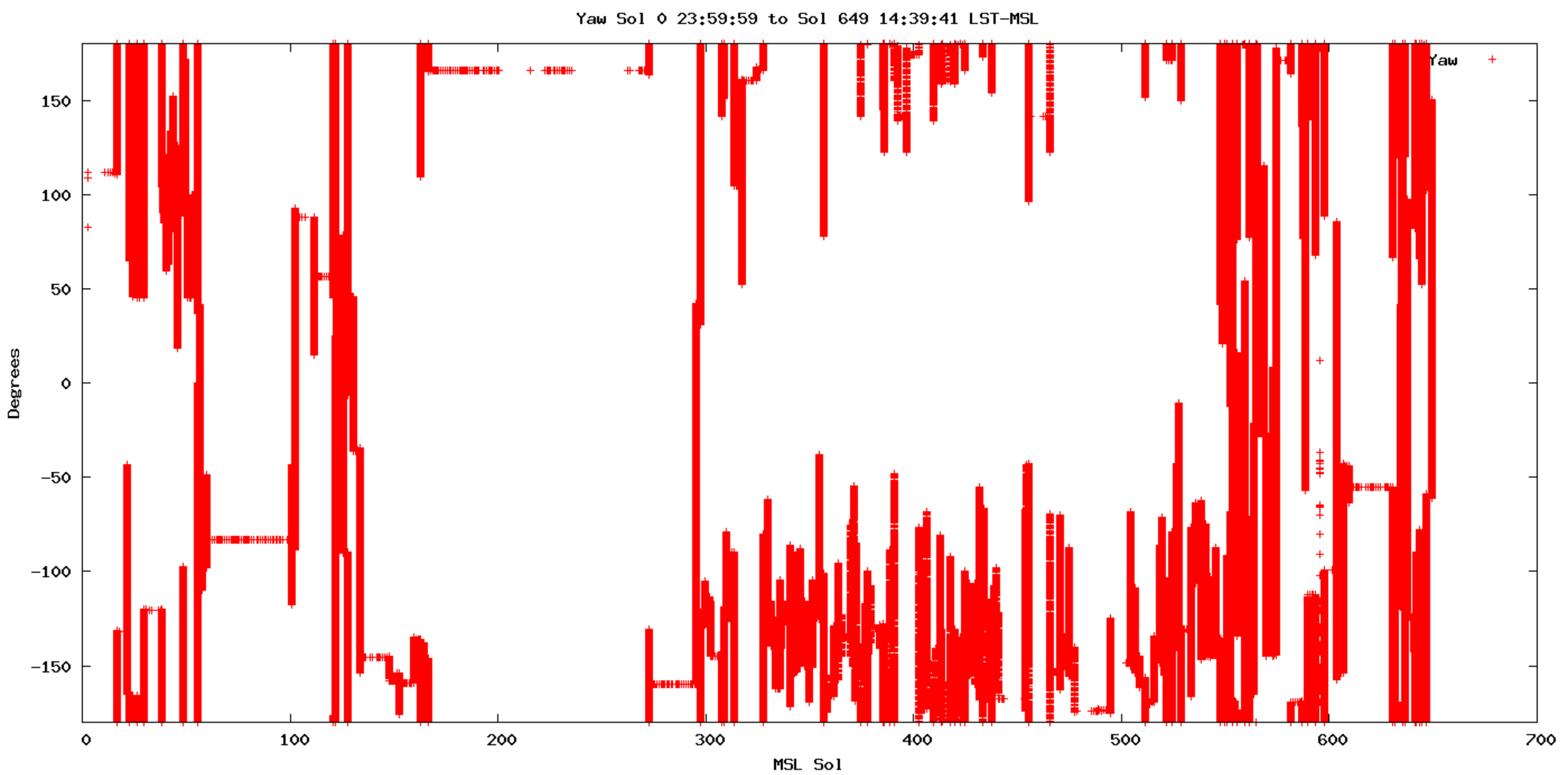
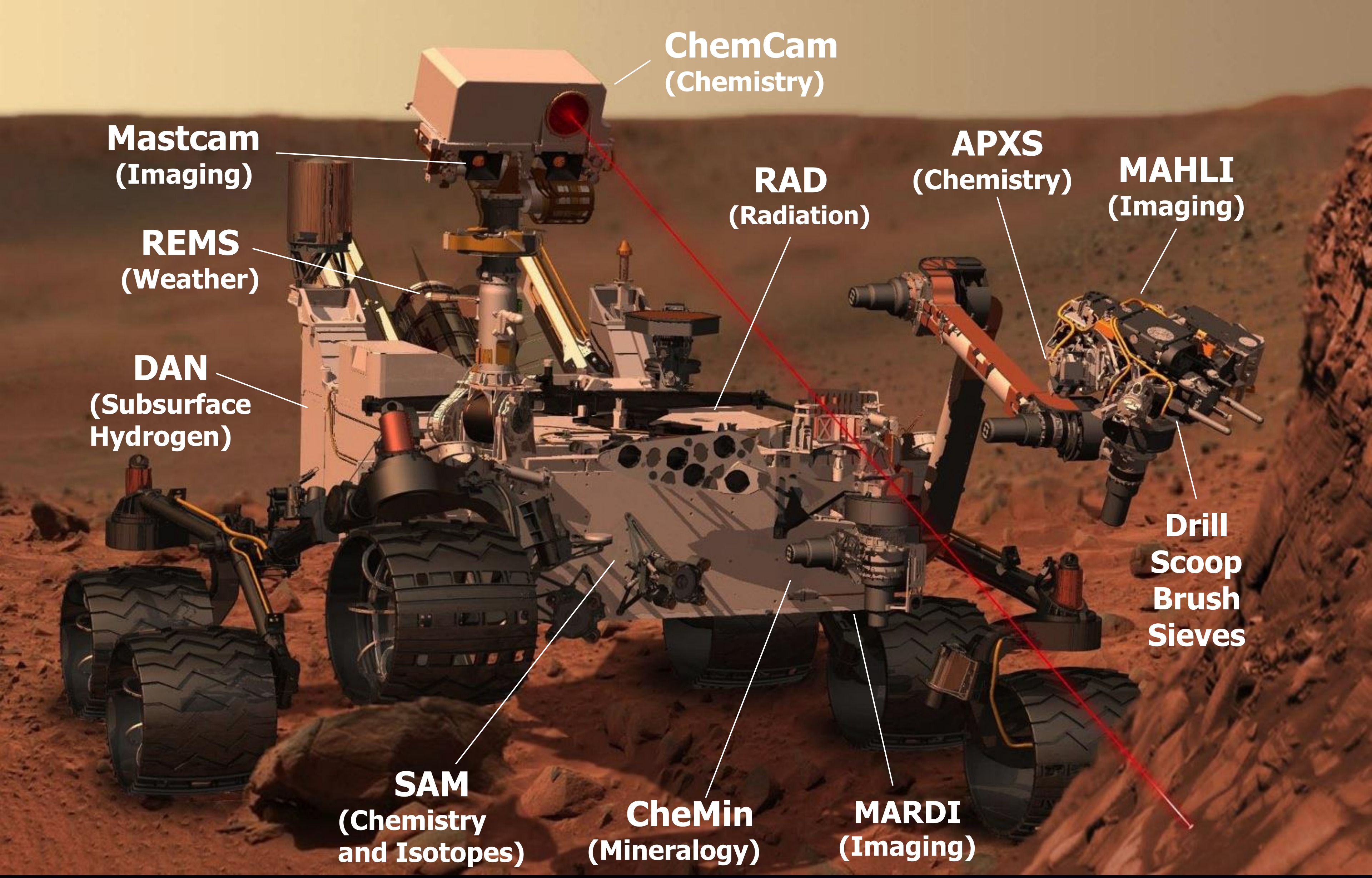
Curiosity Yaw through Sol 650



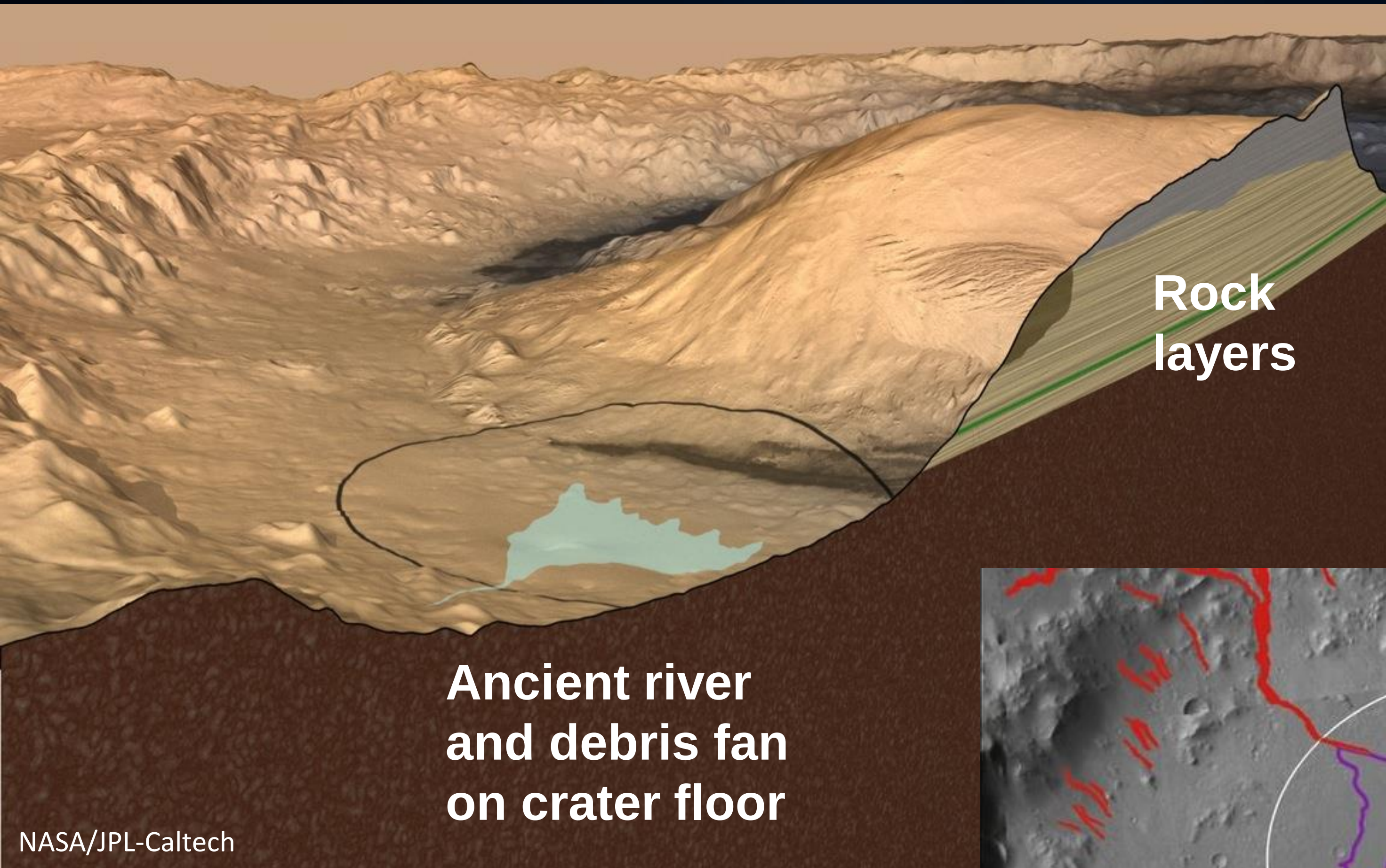
NASA/JPL-Caltech

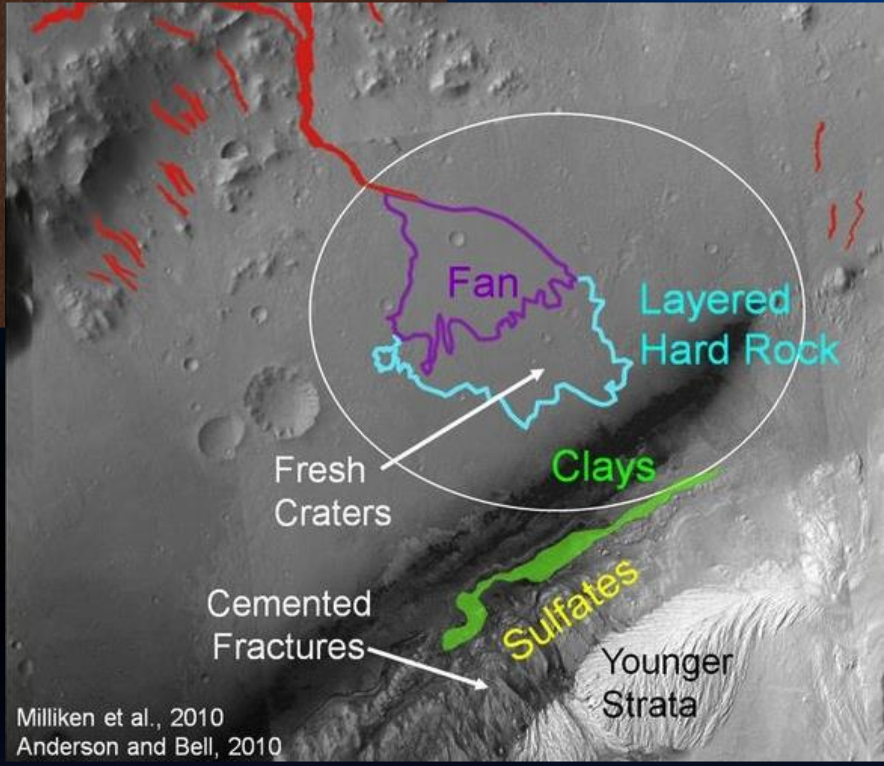


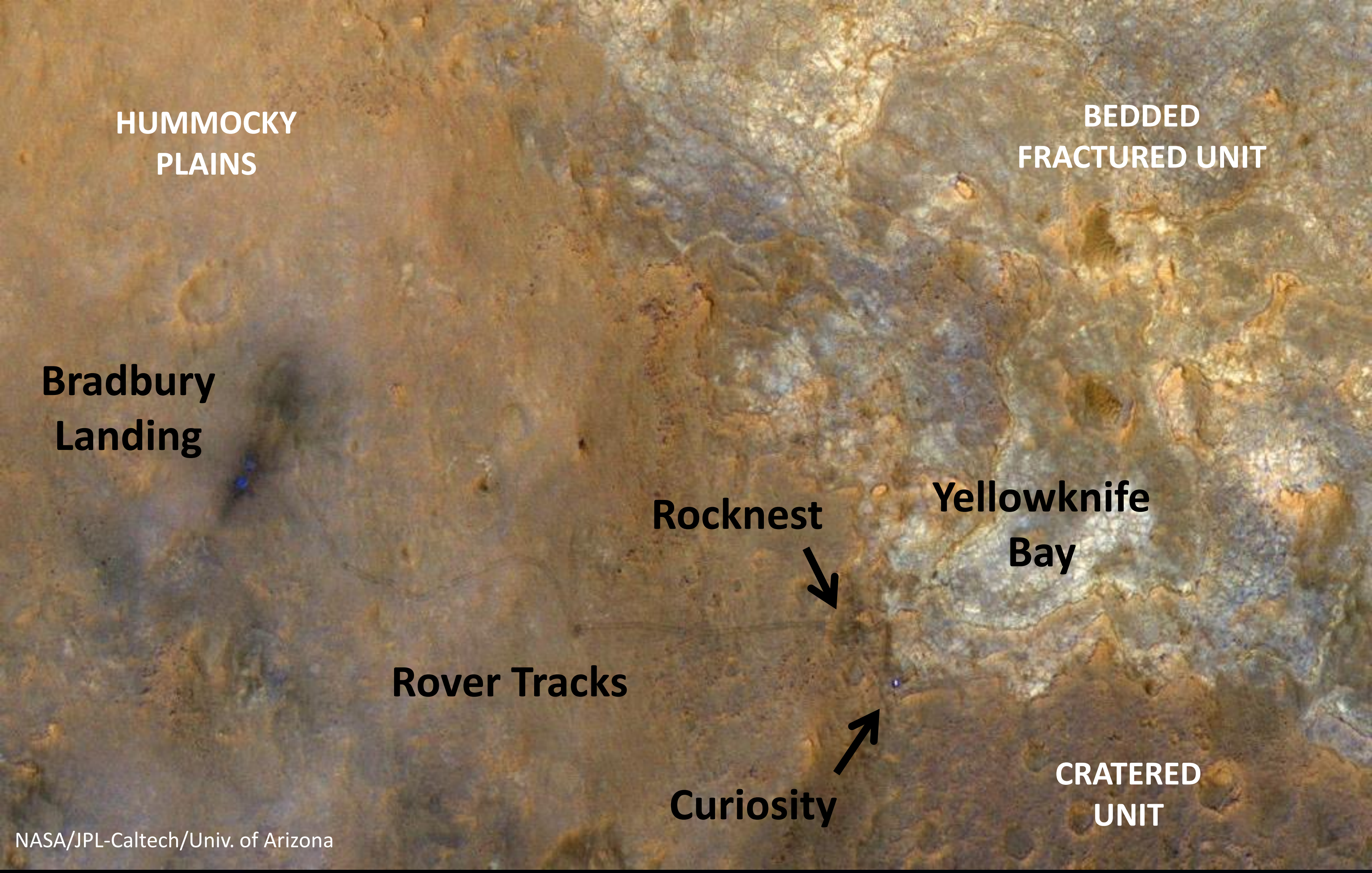
Curiosity's Science Payload

Artist's Concept. NASA/JPL-Caltech

Water-Related Geology and Minerals around Mount Sharp







CURIOSITY

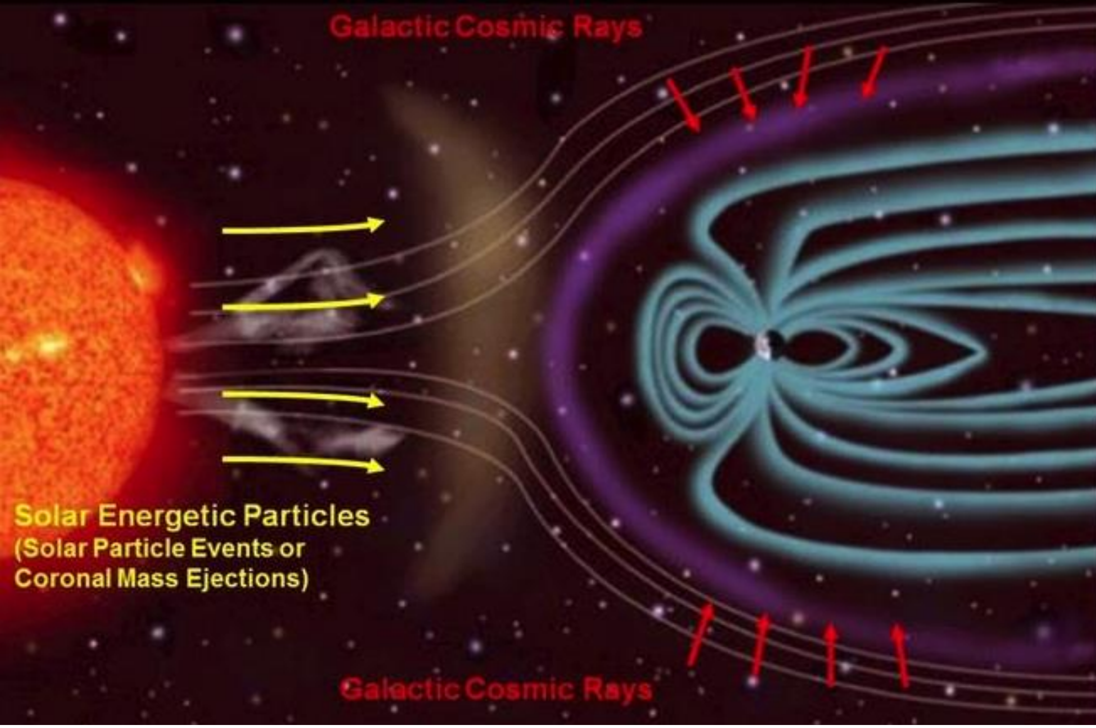
Curiosity and its tracks captured by
HiRISE on the Mars Reconnaissance Orbiter

Rounded pebbles and sand in the conglomerate "Link" indicate water flowed ankle to hip deep

NASA/JPL-Caltech/MSSS

Yellowknife Bay shows a diversity of rock types, fractures, and veins

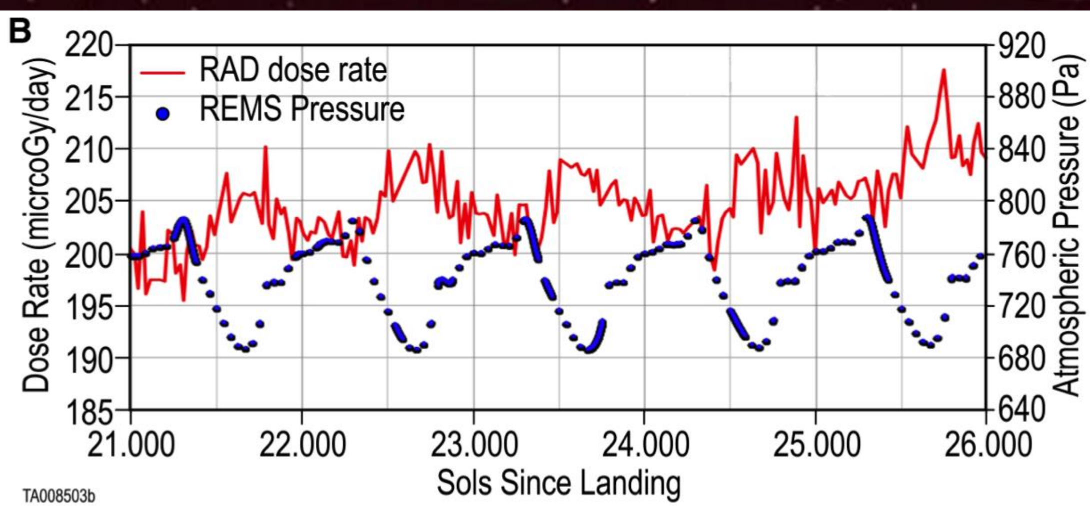
NASA/JPL-Caltech



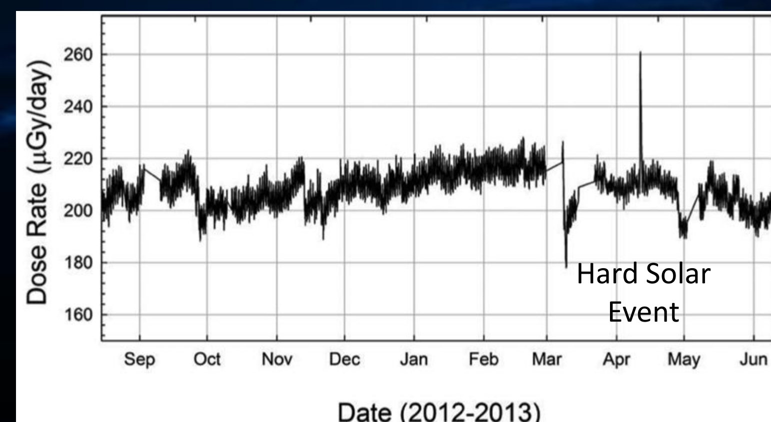
The RAD instrument measured the radiation flux from both galactic cosmic rays and solar energetic particles, in cruise and at Mars’ surface

The surface dose rate is about half that measured in cruise

A crewed mission would receive ~1 Sievert of exposure in a trip to Mars with 500 sols on the surface

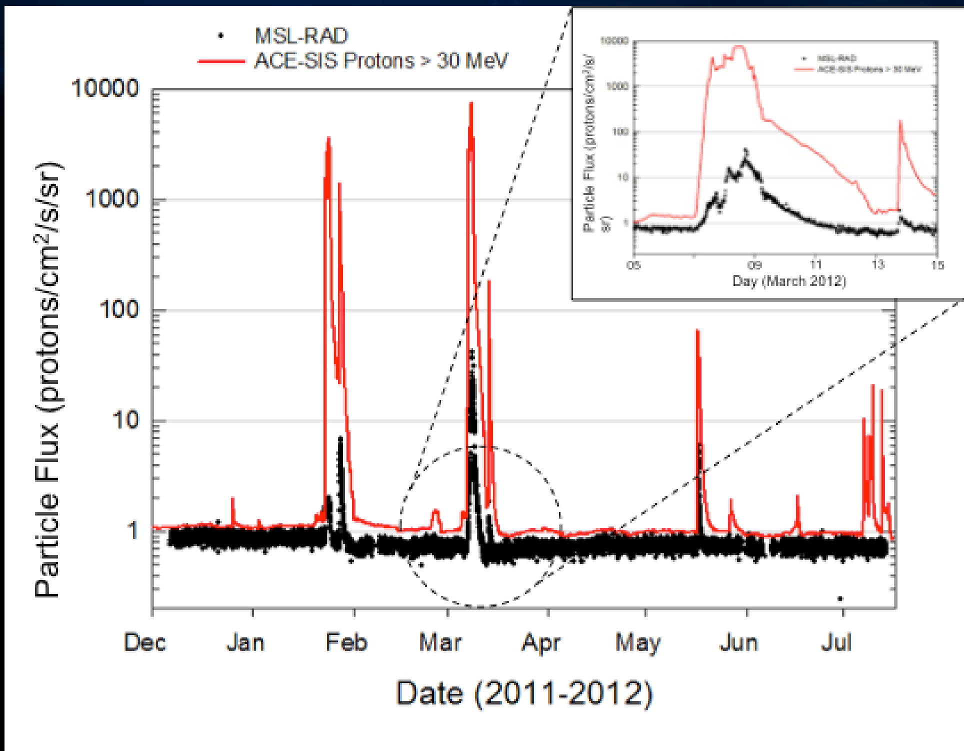


[Hassler et al., 2014]



Curiosity’s Radiation Assessment Detector measures high-energy radiation

RAD & REMS



RAD observed galactic cosmic rays and five solar energetic particle events

RAD is now collecting the first measurements of the radiation environment on the surface of another planet

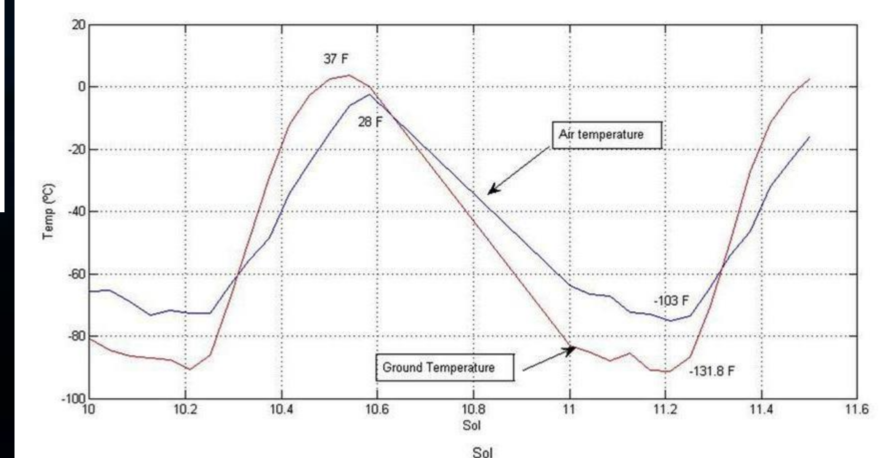
I get Mars weather reports from Twitter

Mars Weather @MarsWxReport 5h

Sol 76 (Oct 23, 2012): Sunny, high -1C/30F, low -72C/-97F, pressure higher at 7.91 hPa, wind E at 7.2kmh/4.5mph, daylight 6am-5pm

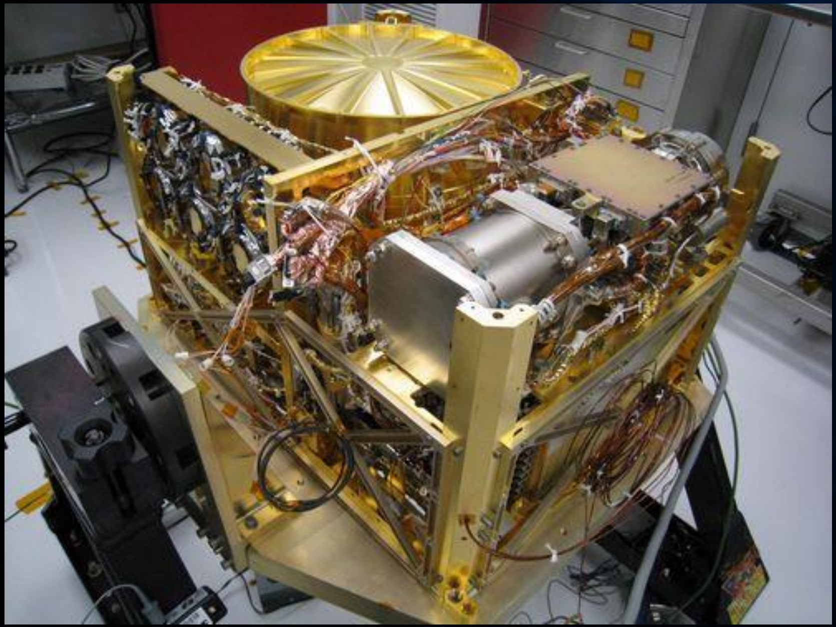
Expand

GROUND AND AIR TEMPERATURE SENSOR



SAM & CheMin

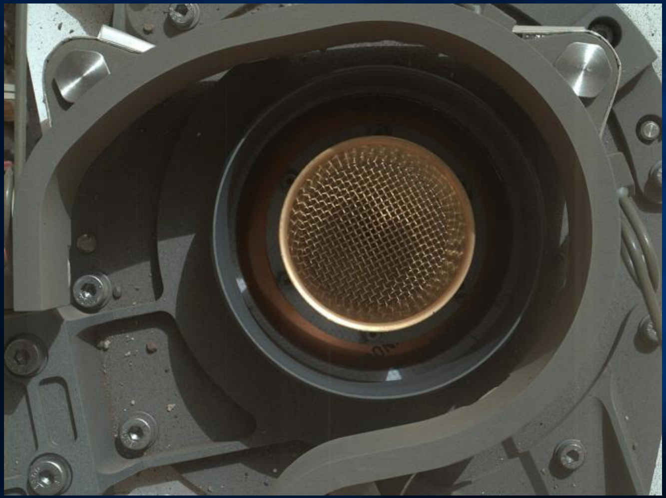
SAM instrument which takes up more than half the science payload on the rover



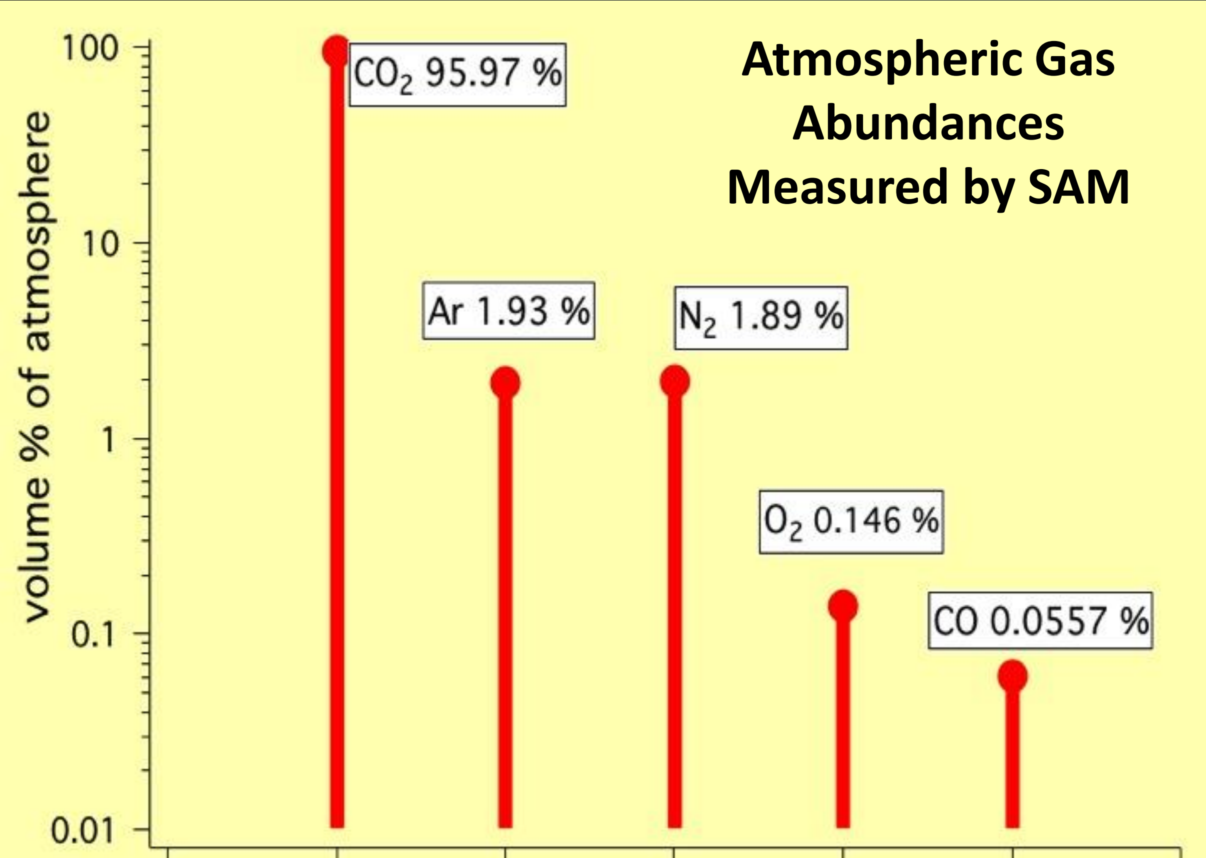
Sample Analysis at Mars (SAM) is the rover's Easy Bake Oven.

It heats soil and rock samples samples until they vaporize and then analyzes the resulting gases

CheMin Inlet



CheMin uses X-rays to determine mineral content and crystal structure of surface samples



NASA/JPL-Caltech/Goddard

SAM found that argon, rather than nitrogen is the second most abundant gas

SAM also found that Mars' atmosphere is enriched in the heavy versions of isotopes, indicating massive atmospheric loss to space

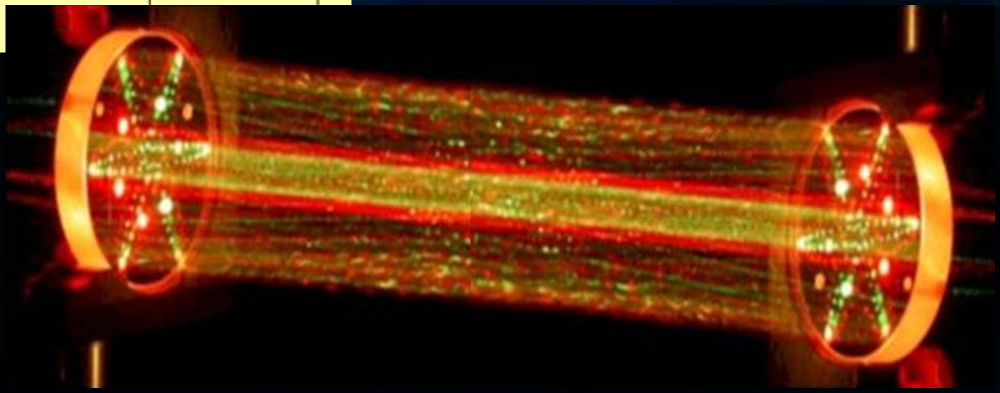
$\delta^{13}C = 46 \pm 4$ per mil

$\delta D = 4950 \pm 1080$ per mil

$^{40}Ar/^{36}Ar = 1900 \pm 300$

Methane has not been definitively detected

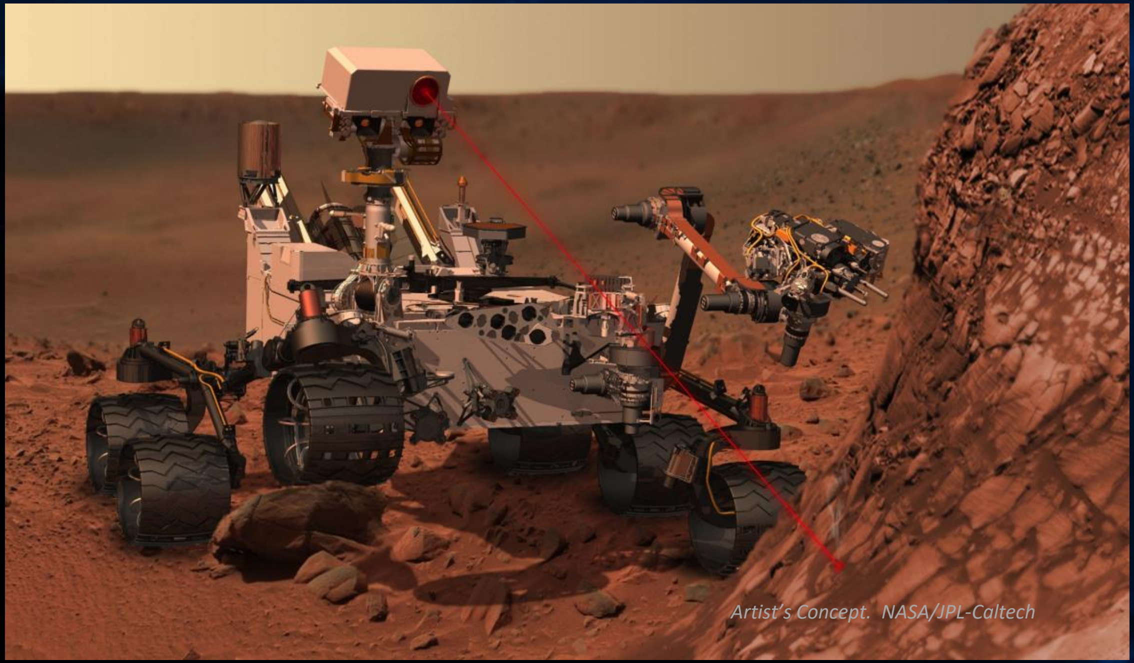
Upper limit = 1.3 ppb

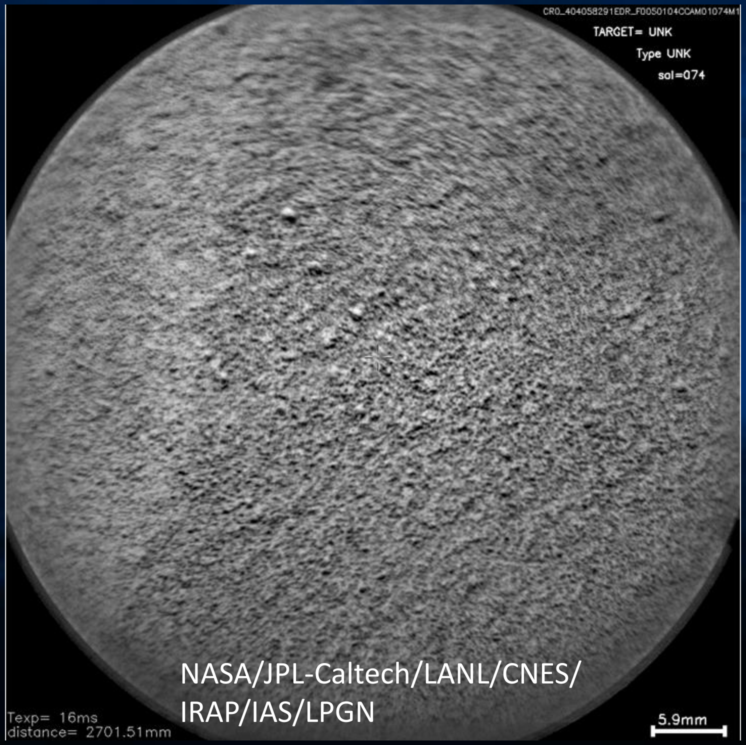


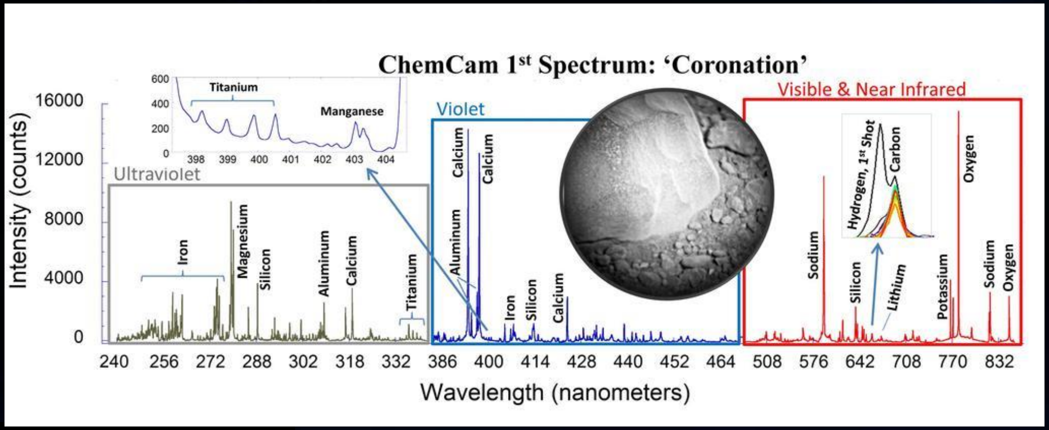
CURIOSITY

The SAM Tunable Laser Spectrometer and Mass Spectrometer measure atmospheric composition

A Laser (ChemCam)







NASA/JPL-Caltech/
U. Guelph

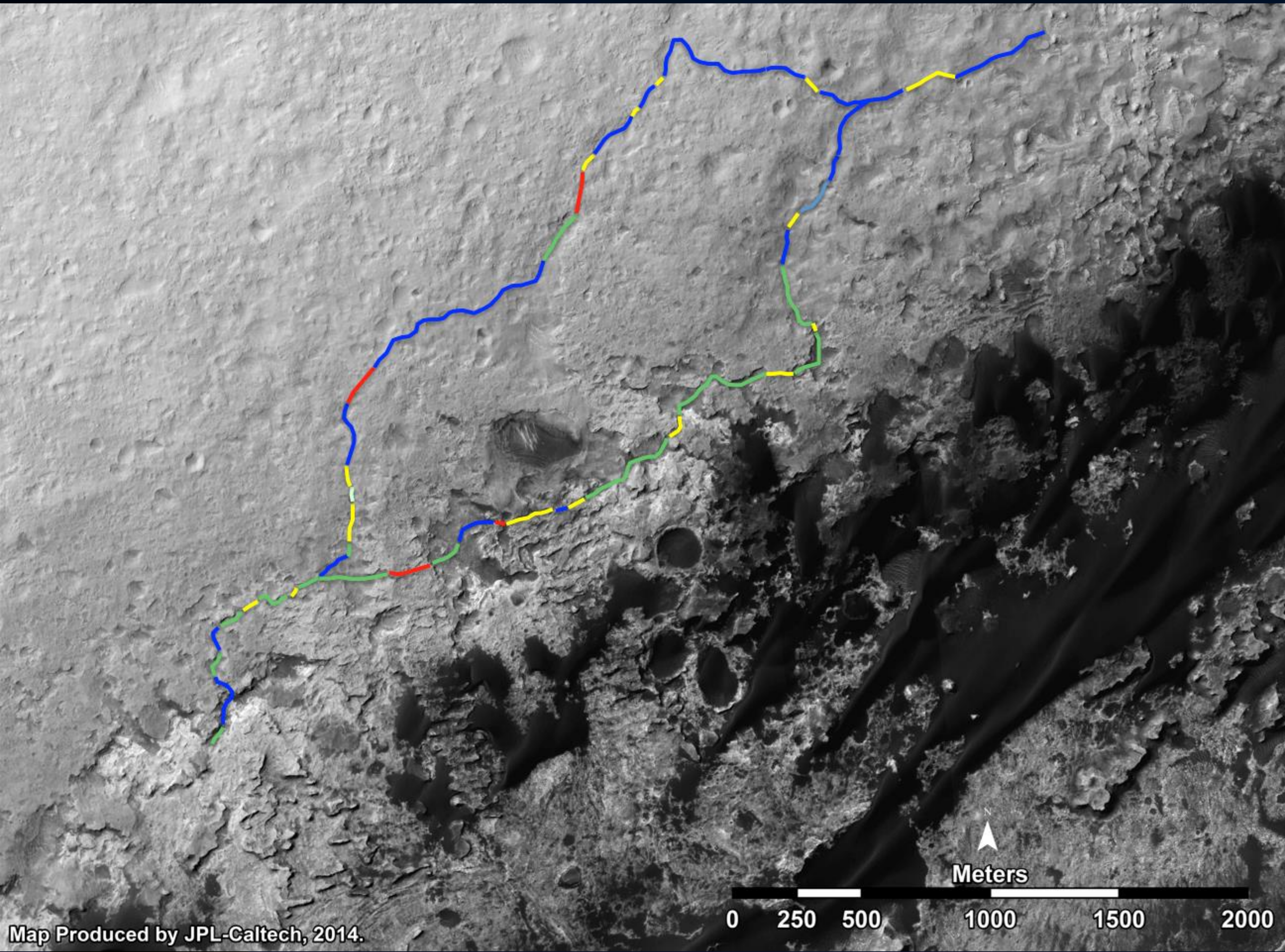
NASA/JPL-Caltech/MSSS

John Klein dime-sized drill hole with light-toned veins and ChemCam profile

An Ancient Habitable Environment at Yellowknife Bay

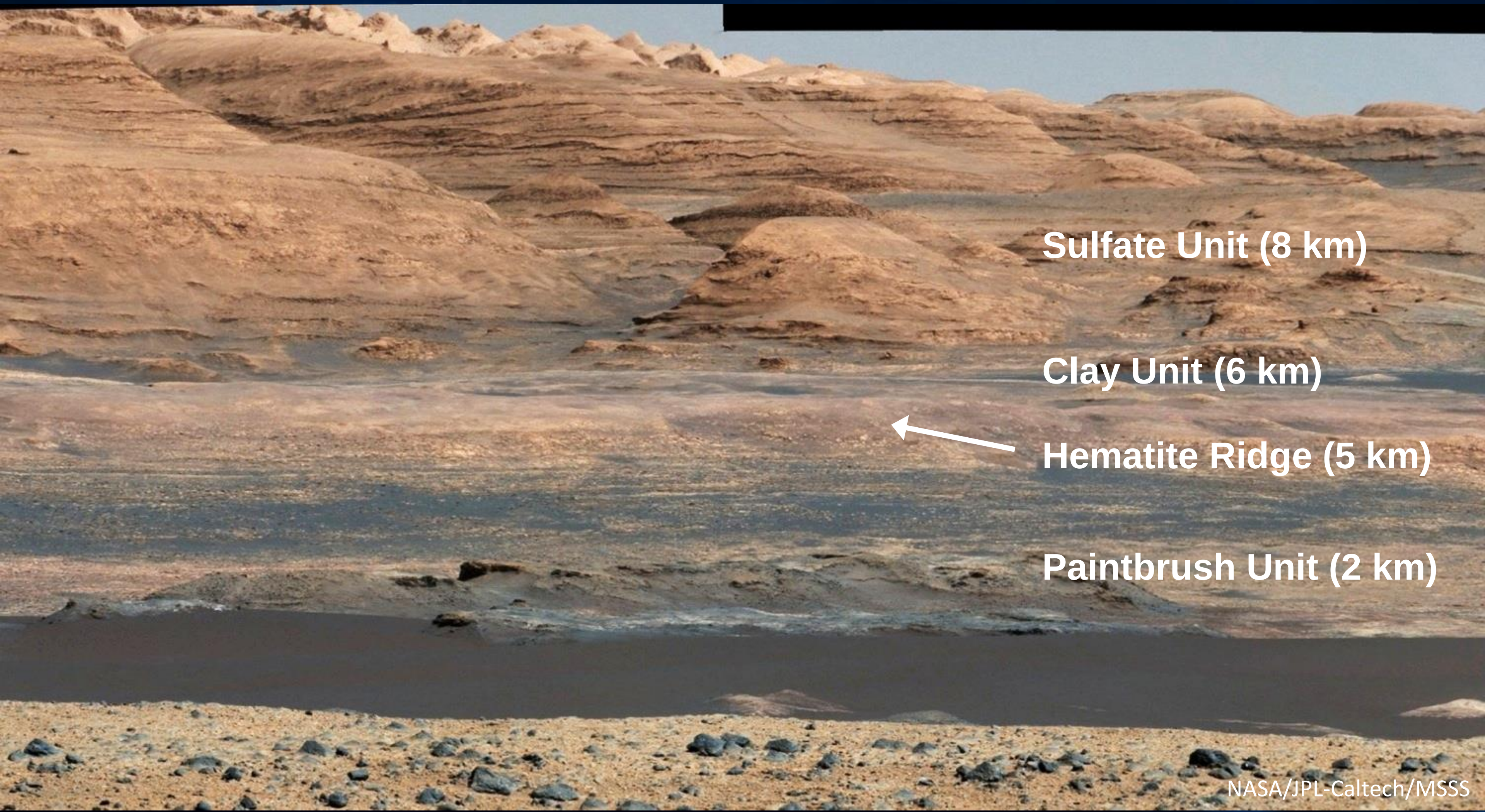
- **The regional geology and fine-grained rock suggest that the John Klein site was at the end of an ancient river system or within an intermittently wet lake bed**
- **The mineralogy indicates sustained interaction with liquid water that was not too acidic or alkaline, and low salinity. Further, conditions were not strongly oxidizing.**
- **Key chemical ingredients for life are present, such as carbon, hydrogen, oxygen, phosphorus, and sulfur**
- **The presence of minerals in various states of oxidation would provide a source of energy for primitive organisms**

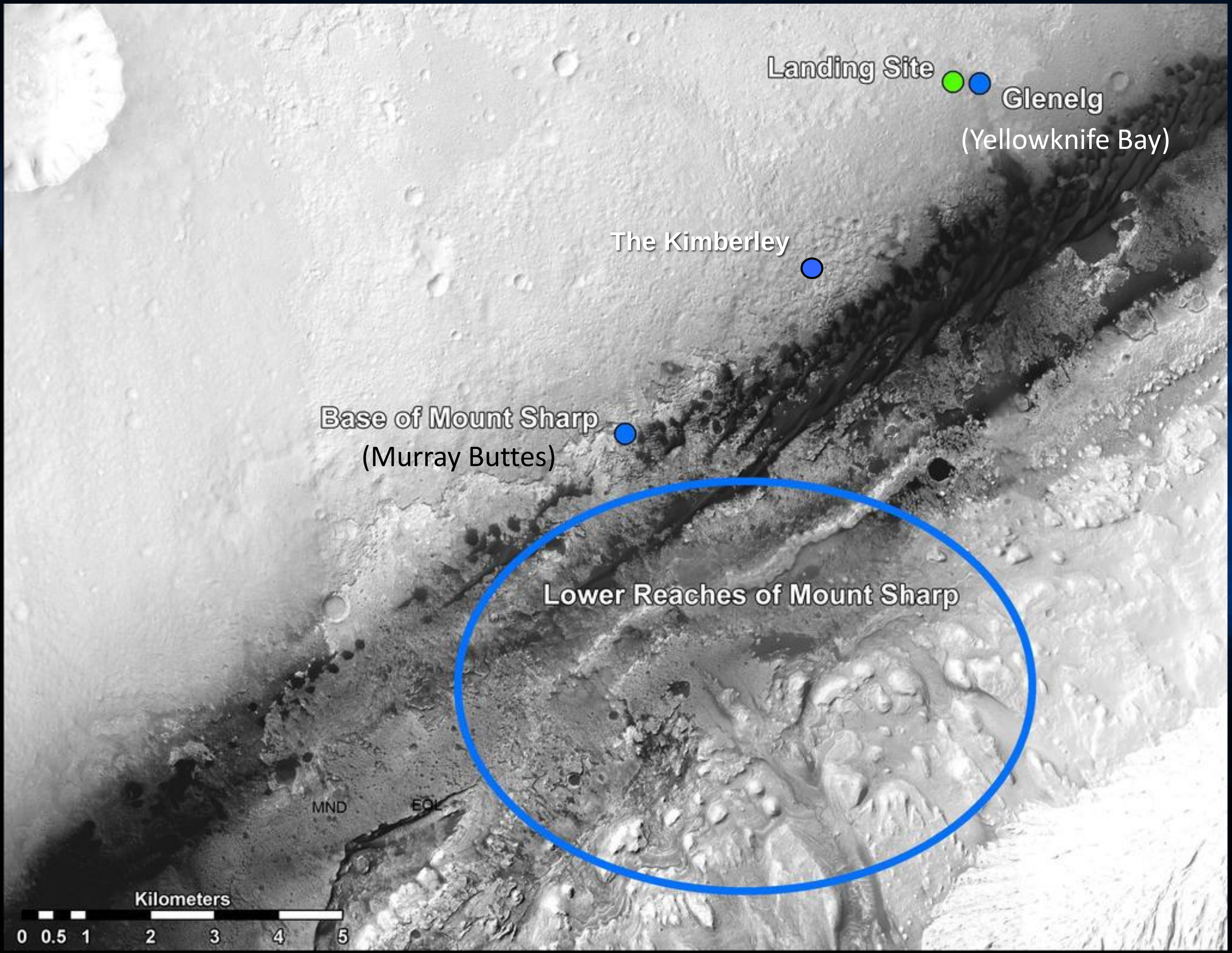
NASA/JPL-Caltech/MSSS


N
Meters
0 250 500 1000 1500 2000
Map Produced by JPL-Caltech, 2014.

The Road Ahead

Targets for Exploration





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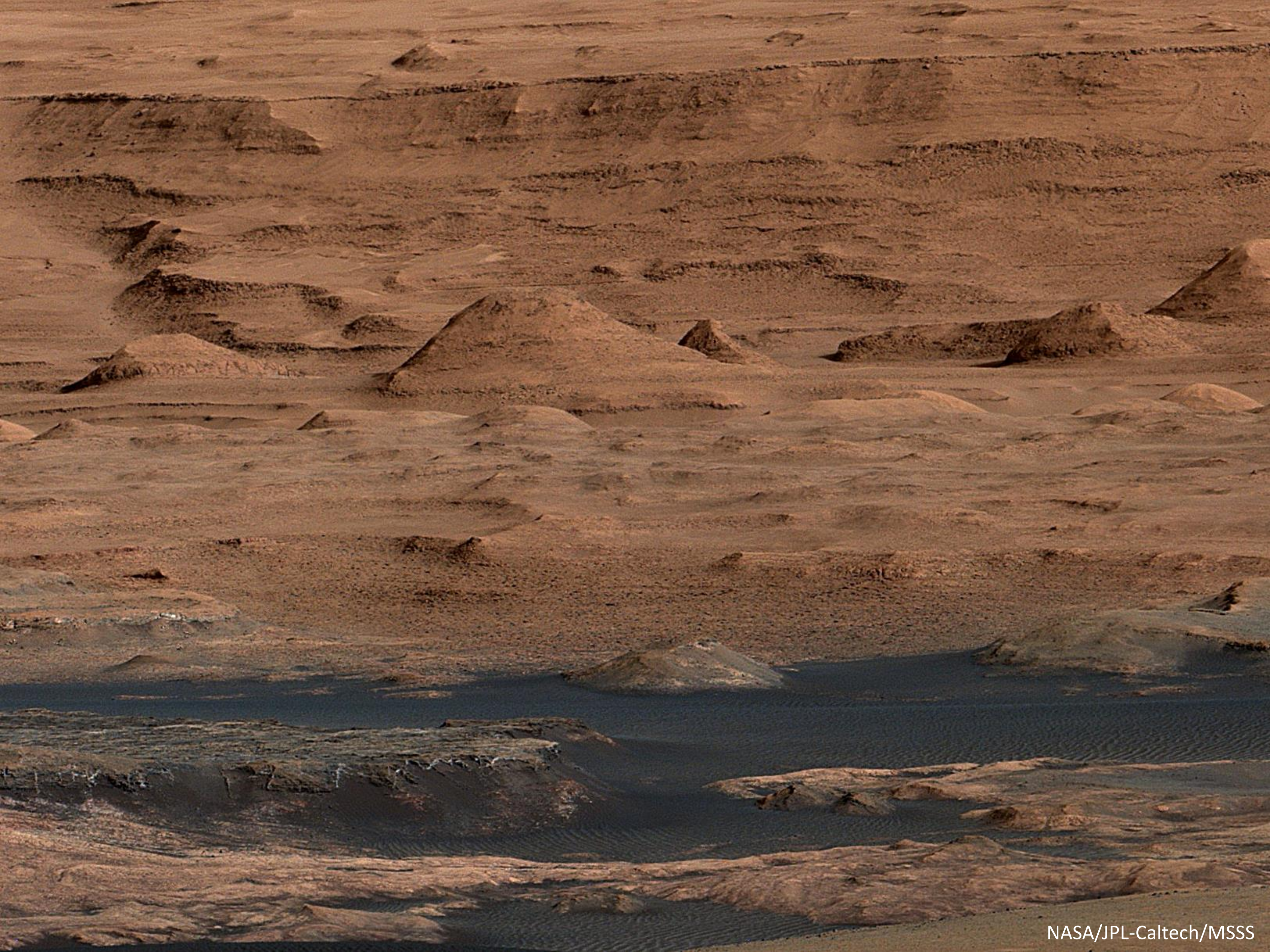
Curiosity’s ultimate goal is to explore the lower reaches of the 5-km high Mt. Sharp



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